# ECONOMIC GEOLOGY

AND THE

## BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS


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# NATURAL RESOURCES AND GEOLOGICAL SURVEYS.[1]

MORRIS M. LEIGHTON.

OUR natural resources deserve the highest and most devoted study. They constitute the foundation of our well being, the means for our protection, our hope for the future.

Man has always been dependent on Nature's storehouse. As he found more and more things which he could use, his desires increased, his own life changed. His consciousness, his awareness, his vision of a better life widened.

We have resources today that were not regarded as resources yesterday. It has been so throughout the ages. As science advances and we employ it to discover and disclose other useful substances, our inventory of resources will further grow.

The geological surveys of this country were born during the formative stages of our science, amid conditions different from the present. Their significance has changed. To that degree which our geological surveys have changed to embody this new significance, to that extent which they are able to command the powers of modern science, they fill their place in present-day society. It is this theme that I have chosen to emphasize.

As an approach to this subject, may we first recall the early period of science, the nature of the times when geological surveys were first established and how they came to be, and then review the transition leading to the present. As Aristotle once said: "He who sees things grow from the beginning will have the best view of them."

## THE ROOTS OF MODERN SCIENCE.

The question of how deep into the past the roots of modern science go, is an engrossing one. Clarity changes to vagueness before we have penetrated very far into history. This is especially true when we pass the epoch-making date of the invention of printing, and again when the relics of handwritten manuscripts give way to the more limited records of archeology.

With assurance we can say that man had no knowledge of geology at the close of the Pliocene or at the beginning of the Pleistocene. The face of the

[1] Presidential Address, presented at the Annual Meeting of the Society of Economic Geologists, St. Louis, Missouri, February 20, 1951.

earth was then untouched except by the forces of nature. The landscape was the product of Nature's artistry. The oceans bore no ships and only birds claimed the air. Then, for the first time in the history of the earth, a single species of animal evolved—man—who was destined to dominate the globe. The knowledge he inherited or received from his antecedents was of no mean order insofar as his habitat was concerned, but his comprehension was without scientific quality as we use the term.

Man appeared in Asia at the beginning of an epoch of climatic changes. As a minor part of the terrestrial fauna, he slowly pushed his frontiers over adjacent lands until, later in the Pleistocene, he had spread over nearly all of the habitable portions of the globe. Gradually and with difficulty he rose above the level of the animal intelligence with which he was first endowed.

With each onset of a glacial climate, within the southward shifting zone of forced migration, further advancement came from differential reproduction which doubtless increased the mental quality of succeeding generations. By the time the fourth ice age arrived, man had an expressed talent for art which indicates the breaking of dawn for civilization.

The broad outlines of what happened in the millennia that follow, around the Mediterranean and along the northern shores of the Indian Ocean, may be conjectured. Regional commerce became interregional, wars united tribes into nations, population centers developed, and the stage was set for science. From now on we can expect evidence of the progress of *Homo sapiens* toward his crowning achievement—that of understanding the world in which he lives.

It is doubtful, however, if the progress of the historical period can be represented by a smooth upward curve. The initial light of science lit by the Greeks during the Classical Period was nearly extinguished during the Dark Ages by the political changes that ensued and by the repressive dictum of the established Church. And if the events of the prehistorical period could be made known, we might find that the Greek philosophers were by no means the first to possess some of their advanced concepts.

The attainments of the Greeks were preserved apparently by the Arabians through the Dark Ages as a result of their military conquests. In the eleventh century A.D., the Arabian philosopher, Avicenna, the "Prince of Physicians," held to the interpretation that some highlands are due to uplift while many peaks and steep ridges are remnants of hard rocks left by prolonged erosion of soft, weak rocks, and that mountain soil possibly contains material which once was in the sea that formerly overspread the land. Says Fontani: "The age of Arabian learning continued for about five hundred years and was coeval with the darkest and most slothful period of European annals."

The subsequent pace of intellectual progress, when seen against the million years of man's existence, was accelerative. The few centuries that remained for learning to reach the level of modern science was less than one-tenth of one percent of the whole Age of Man. His creative genius has always distinguished him, but because his knowledge of the world started at the animal level and because new concepts suffered a heavy toll until means for preserving them were achieved, advancement was inevitably slow during his early history for millennia upon millennia.

Seneca, Roman philosopher of the first century A.D., said: "Nature does not reveal all her secrets at once. We imagine we are initiated in her mysteries; we are as yet but hanging around her outer courts."

## THE RENAISSANCE OF SCIENCE.

For our purpose, however, within the limited scope of this paper, the Renaissance of the 15th century will serve as a practical beginning date for discussing the preparation of modern science for the first geological surveys. There was no prevailing philosophy of natural science. Instead, magic and witchcraft prevailed—the evil children of Ignorance and Superstition. Man had come to believe during the Dark Ages in mysterious and unknown forces and the established Church was intolerant of any scientific pronouncements opposing the orthodox interpretations. There was no scientific climate.

Leonardo Da Vinci, however, possessed great mind and skill. Not only did he produce paintings—*Mona Lisa* and *The Last Supper*—which captured the hearts of the people and were treasured by the Church, but he had a rational approach to the phenomena of nature. To him, as to some of the Greek philosophers, fossil shells in the rocks were the remains of forms that once lived in the seas, when the land was beneath salt water, and that were covered by sediments washed from the lands of that time. From his experience as an engineer, he pointed out that groundwater was not a primitive constituent of the earth but had its origin in rainfall and that it circulated widely through porous strata. Da Vinci also laid some of the groundwork for physics and chemistry by studying falling bodies, developing the concept of work from force, interpreting sound as wave motion in air, finding that air is divisible into combustible and uncombustible constituents, and by other discoveries.

Christopher Columbus, a contemporary of Da Vinci's, upon his return from his voyage to America, taught that the earth was a circumnavigable globe.

Copernicus was born only 22 years later than Da Vinci. He gave mankind a new picture of the world. The earth is not the center of the universe but a member of a family of planets revolving about the sun, rotating on its axis, thereby giving us night and day. The fixed stars, he disclosed, are not set in a firmament enclosing a relatively small sphere but are at such great distances in space that they appear to be fixed.

Thus man approached the overwhelming conception of the infinity of the universe.

Georgius Agricola, a young man when Da Vinci died, made an extensive study of mines and ore deposits, became the world's first mining geologist and metallurgist, and wrote several books on physical geology, subterranean waters and gases, systematic mineralogy, mining and treatment of ores, and a glossary of Latin and German mineralogical and metallurgical terms. He ignored Aristotle's speculations on the influence of the stars on stones, gems, and metals and prepared a fairly rational statement on the part played by mineral-bearing solutions in the deposition of ores and in the cementation of rocks. Unfortunately he could not draw upon modern chemistry and crystallography.

Galileo made his appearance in scientific circles about 40 years later. He confirmed and extended the findings of Copernicus, introduced the use of the telescope, uncovered a new wealth of information on the solar system and the Milky Way, and founded the whole science of motion.

### PROGRESS IN THE 17TH CENTURY.

The 17th century had its great disciples of science. Descartes founded analytical geometry. Guericke made the air pump, worked with the phenomena of air and vacuum, and added to knowledge concerning atmospheric pressure and its movement, the nature of propagation of light and sound in air and the relation of air to combustion and to life of animals. He also discovered electrical repulsion.

Boyle discovered his law of gases and helped to lay the foundations of analytical chemistry. Mariotte laid the basis of our knowledge of the distribution of pressure and density in the atmosphere and of measuring altitude by the barometer, initiated the study of hydrology, and explained the origin and nature of clouds.

Nicolaus Steno, after studying medicine at Copenhagen and becoming physician to the Grand Duke of Tuscany, devoted much time to a study of the beaches, quarries, and outcrops in the hills of central Italy, and published what was, for his time, a remarkable treatise on the geologic history of Tuscany in which he recognized successive epochs of submergence, sedimentation, uplift and erosion.

Isaac Newton's revolutionary work also came partly in the 17th century and in the 18th. By observation and mathematics he discovered the laws of universal gravitation—valid, he proclaimed, for all matter in stellar space—and explained the motions of the heavenly bodies, the shape of the earth, the opposite tides of the earth, the relationship between the masses of the earth, moon and sun, the masses and specific gravities of the sun, planets, and some of the satellites, the motions of the earth's axis and the precession of the equinoxes, and discussed the question of the movement of the solar system through space. He also founded differential and integral calculus, the science of acoustics, and developed the fundamental principles of hydrodynamics and aerodynamics. These contributions made by one man are amazing.

### EMERGENCE OF GEOLOGY IN THE 18TH CENTURY.

That the science of geology should emerge in the last half of the 18th century following the rationalism already developed was natural. Up to this time the geological features of Italy were the basis for the development of historical geology and stratigraphy. Now the scene shifts to France and the British Isles. About the beginning of the 18th century, Guettard, a physician who was also interested in botany and plant ecology, became intrigued with the habitat relationships of certain plants to certain rocks and eventually devoted his study to the rocks themselves. In his memoir of 1752 upon the rock formations surrounding the Paris basin, he recorded their sequence and he inferred that they

once were continuous with similar strata across the English Channel and the Straits of Dover into England. He showed that each formation carried its own mineral resources, which was one of the earliest approaches to a natural resource survey. He later made a map showing the distribution of rocks and minerals from North Ireland to Spain and the Mediterranean, and he also studied their fossils and recognized the erosional processes of streams, groundwater and waves in terms of the past and of the present. He discovered the extinct volcanoes of south central France and identified their products of pumice, scoria and sheet-flows and the inter-bedded soils which he asserted recorded time intervals between episodes of volcanism.

Desmarest followed him in the mapping of the volcanoes and their flows and in 1775 wrote on the theme of streams eroding their own valleys instead of finding them ready-made. This paper, however, was not published until 1806, 18 years before the first American geological survey was established.

Linnaeus, the Swedish botanist, began the renaissance in paleontology about the mid-portion of the 18th century by introducing the binominal system of naming organisms, both living and fossil.

Saussure started the general usage of the terms *geology* and *geologist* in 1779. Being a follower of Werner, who held that the primitive rocks were chemical precipitates in a universal ocean, his love and study of the Alps fell short of contributing all that they might, but it was he who guided Hutton to the summit of the Alps where he gained a tremendous impression of the geologic processes in operation there.

Hutton's presentation of his "Theory of the Earth" to the Royal Society of Edinburgh in 1785 marked a turning point in geology. He, a doctor, scientific farmer, and manufacturing chemist, maintained that the earth changed often and greatly; that conglomerates, sandstones, shales, and limestones could be matched by deposits now being laid down; that a conglomerate was a gravel cemented into stone, a sandstone indurated sand, shale compacted mud, and limestone consolidated fragments of shells and corals; that much rock which now appears on the land was accumulated in the sea; that every age had these sediments; that uplift had caused some rocks to stand on end or be overturned, and many to be folded; that secondary strata were deposited upon tilted strata as is being done today; that some strata had been changed by heat and recrystallization—a concept that foreran the concept of metamorphism announced by Dana 40 years later; and that some rocks were made by lava flows and intrusions into older rocks now eroded away. To him the earth revealed no trace of a beginning, no prospect of an end.

In 1802, Playfair, a more talented writer than Hutton, made a terse, dramatic re-presentation of Hutton's ideas. He emphasized Hutton's principle that the earth's present features and its changes explain its past. His book caused a sensation and helped lead to the rejection of the widely spread Wernerian doctrine.

William Smith, the English civil engineer, brought crowning achievement to 18th-century English geology by his discovery that different fossil faunas distinguish strata of different ages. At the request of Reverend Benjamin Richardson, in 1801, he dictated his "Card of the English Strata" which was

distributed to other workers. He published his geological map of England and Wales in 1815.

### CHEMISTRY AND PHYSICS BECOME THE HANDMAIDENS OF GEOLOGY.

Not until the latter part of the 18th century did chemistry and physics come to the aid of those working in geology. It must be emphasized, however, that the works of Copernicus, Galileo and Isaac Newton contributed tremendously to rational views of the world as a whole.

The science of chemistry was founded by Black, Scheele, Priestley, and Cavendish in the latter half of the 18th century, but much remained to be done. Electrical and magnetic forces were also explored at this time, together with means for their measurement. Infra-red rays and ultra-violet rays were discovered at the beginning of the 19th century. Dalton discovered the existence of atoms and initiated the Atomic Table in 1808.

### GEOLOGICAL WORK IN NORTH AMERICA IN THE 18TH CENTURY.

Geology was brought forth in its swaddling clothes in Europe and not in America. There were no men in America comparable to Guettard, Desmarest, Linnaeus, Hutton, Playfair, or William Smith. A favorable atmosphere for science was generally lacking. Acceptance of the literal teachings of the Bible was general and most of the teaching of science, such as it was, was done in the medical schools.

Following the Revolutionary War, however, the new national spirit gave rise to sentiment for natural resource studies. This interest was increased by the personal contacts and publications of Dr. Johann Schöpf, who had come as a surgeon with the Hessians and remained to tour the East and Southeast after the peace of 1783; Comte de Volney, a learned traveler and historian from France; and William Maclure, an educated businessman and philanthropist from Scotland. It was unfortunate that Maclure brought to America the teachings of Werner rather than of Hutton, the "Father of Geology"!

### GEOLOGICAL SCIENCE IN AMERICA AT THE BEGINNING OF THE 19TH CENTURY.

There was no one in America trained in geological observations, no geology was taught as a science, libraries were few and small, to what extent they contained European scientific literature is not known, there were no accurate maps outside of New England and the eastern Atlantic states, most of the continent was still a wilderness, such geological classifications and interpretations as were made were against the background of Wernerism and Biblical teachings, and unfortunately many of the geological initiates were obliged to cut their eyeteeth on some of the most difficult geology in the United States.

At first most of the "scientific" papers were pseudo-scientific and reflect readiness to theorize and respond to personal religious beliefs. The early workers were men of other learned professions, and so erroneous identifications were common. In 1800, although Harvard University was 164 years old, Yale 99, Columbia University and University of Pennsylvania 46, and the state uni-

versities of Tennessee and North Carolina had just been started, there were no departments of geology in these American universities.

The first to take the step was Yale University when Benjamin Silliman was appointed Professor of Chemistry and Natural Science in 1802. Being of classical training only, he went to Philadelphia to attend the Medical College. After taking five months of chemistry, anatomy and botany, he gave his first lecture at Yale, April 4, 1804. He soon went to Europe to purchase scientific books and apparatus, to meet scientists and to attend lectures given by followers of both Hutton and Werner. He founded the *American Journal of Science* in 1818.

Parker Cleaveland, a graduate of Harvard, was appointed Professor of Mathematics, Natural Philosophy, Chemistry and Mineralogy in Bowdoin College, Brunswick, Maine, in 1805, with little or no training for the position. Becoming deeply interested in mineralogy, he published the first American treatise on mineralogy and geology in 1816. He emphasized chemical composition as the most important basis of mineral classification.

Papers mainly on local geology also appeared at this time by S. L. Mitchill, J. F. and S. L. Dana, Edward Hitchcock, John H. Kain, Amos Eaton, Henry Schoolcraft, Edwin James, Benjamin Silliman, J. B. Gibson, D. H. Barnes, John Finch and others. These covered various sections of the United States from Massachusetts to the Missouri Ozarks and the headwaters of the Mississippi. Few settled down to exhaustive studies of local areas.

Thomas Say, a biologist, was the first American, according to Schuchert, to point out (in 1819), in his "Observations on Some Species of Zoophytes," that "the progress of geology must be in part founded on a knowledge of different genera and species . . . which the various accessible strata of the earth present."

Rensselaer Institute was established late in 1824 with Amos Eaton as Professor of Chemistry and Experimental Philosophy as well as lecturer on geology, land surveying, and the laws governing town officers. It was here that James Hall graduated in geology and chemistry in 1832 at the age of 21.

## THE BEGINNING OF STATE GEOLOGICAL SURVEYS.

It was under these primitive conditions of the science that state geological surveys were established to inform the people of their natural resources. Interest spread from Maine to Michigan, Massachusetts to Tennessee, and south to the Carolinas. The two Carolinas made the initial effort in 1824 and 15 other states during the decade from 1830–1839—Massachusetts in 1830; Tennessee, 1831; Maryland, 1833; Connecticut, New Jersey and Virginia, 1835; Maine, New York, Ohio, and Pennsylvania, 1836; Delaware, Indiana and Michigan, 1837; Kentucky, 1838; and New Hampshire and Rhode Island, 1839.

The more populous area was from Boston to Baltimore; the mountains nearby were a wilderness. Emigration was rapid along the more easily traveled routes to Ohio, Michigan, Indiana, Kentucky, and Tennessee and thence to Illinois, Wisconsin, Iowa, and Missouri.

These were days of expansion and development. The Erie Canal was opened in 1825; nearly 3,000 miles of railroad were laid by 1840. Improvement of existing roads, construction of new ones, promotion of soil fertility, and dreams of finding valuable ores gave impetus to the cause of natural resource surveys.

But state revenues were small and the industrial basis for utilizing the information was slender. There also prevailed the thought that only one, two, or three years were sufficient to make a complete survey of a state. All plans were of a temporary nature. State leaders had no concept of a geological survey as a permanent institution designed to accumulate and disseminate information continuously and to enlarge and preserve collections having future scientific and industrial value. The results, they thought, could be written up and published, wrapped in a package and entrusted to state officers and legislators for distribution and thus the project would be completed and terminated. Henceforward there would be no further need, they thought, for investigation. Any new industrial enterprises or the needs of the rising generation were not in mind.

Consequently the tenure of most of the early geological surveys was ephemeral. Many were re-established, some several times, and their re-establishment bears testimony of renewed interest and faith in the soundness of the principles involved.

There were other aspects of the times that affected these early organizations. The geological profession was small and confined largely to colleges and universities. Therefore it was natural to attach geological surveys to state universities where the chief authority on the science could be found to guide and pursue the investigation. The results of the preceding summer's work could be written up into a report in connection with teaching duties and inquiries could be answered. If appropriations failed there would still be some continuity of service for the public. Likewise there was both economy of operation for the state and enrichment of knowledge for the professor in his teaching of the subject.

Not all of the surveys were given this attachment to universities. The Geological Survey of New York was an outstanding example, but this survey was unique in many respects. Its great leader, James Hall, was inspired by what the geology of New York held for science, in its classic section of the Paleozoic system, and being free to give his chief attention to what he considered to be the Survey's objectives, he pressed forward for continuing support and successfully appealed to the pride of state authorities except for a few years when he carried on indomitably on his own resources. Adhering to fundamental work in stratigraphy and paleontology and convinced of the contribution which the state through him was rendering to science, he made the New York Geological Survey a unique one in the annals of American geology.

The organization of surveys continued decade after decade as the number of states increased. The chronology of those later than the ones mentioned above follows:

1840–49 Alabama, Vermont
1850–59 Arkansas, California, Illinois, Iowa, Mississippi, Missouri, Texas, Wisconsin
1860–69 Kansas, Louisiana, Minnesota, Nevada
1870–79 Colorado, Georgia
1880–89 None
1890–99 Nebraska, North Dakota, South Dakota, West Virginia
1900–09 Florida, Oklahoma, Washington, Wyoming
1910–19 Arizona, Idaho, Montana, Oregon
1920–29 New Mexico
1930–39 Utah

Hall exerted marked influence on many of the surveys that were organized from 1840 to 1870. These emphasized stratigraphy and paleontology but included economic geology. A. H. Worthen, who worked with Hall in Iowa before succeeding J. G. Norwood as State Geologist of Illinois in 1858, believed that the first element in the program of a state geological survey for a state like Illinois was basic stratigraphy and paleontology but that this work should be accompanied by a study of the economic geology. Accordingly in Illinois he employed a staff from time to time consisting of an invertebrate paleontologist, F. B. Meek, a vertebrate paleontologist, J. S. Newberry, a paleobotanist, Leo Lesquereux, several geologists for work on county reports, and a mining geologist, J. D. Whitney, who later became state geologist of California. Although this work was of both a fundamental and economic character and is useful even at the present time, the industrial conditions were inadequate in their demands for geological information and appropriations ceased for field work in 1875 and for publications in 1890. Provision of physical facilities were so meager throughout this period of time that they failed to give the identity to the Survey that it deserved as an institution. This was generally true for the other state surveys of the country during most of the 19th century.

However, there was rapid improvement in the work done as a result of great progress in geology and chemistry, of improvement in field observation and laboratory technique, of extension of detailed studies, and of greater international contact.

Charles Lyell, Charles Darwin, and Louis Agassiz brought to the scientific world penetrating and revolutionary views. They were powerful teachers and lucid writers. The doctrines that the present is the key to the past, that geologic time and changing environments account for the evolution of life, and that continental glaciation had transgressed millions of square miles in Europe and America during the Great Ice Age gave geology a maturity and expansiveness hitherto lacking. New techniques for a penetrating study of crystals, minerals and rocks came from Nicol, Zirkey, and Rosenbusch. The geologic periods of the Paleozoic Era were largely resolved on a stratigraphic basis by Sedgwick, Murchison and Barrande.

In America, J. D. Dana, Sir William Logan, James Hall and others were rising as leaders in physical geology, pre-Cambrian geology, and in paleontology and stratigraphy.

American literature was rapidly growing and European literature was widely available. The mineral industries were showing signs of growth. Manufacturing and commerce were expanding. The Union-Central-Pacific railroad was completed to the Pacific Coast in 1869, and by 1873 railroad mileage in the United States had reached 63,000 miles.

### EARLY ACTIVITIES BY THE FEDERAL GOVERNMENT.

Subsidiary geological work was done by the Federal government from 1819 until 1867, in connection with a series of military explorations. These expeditions were sent into the Northwest Territory, the Ozark Mountains, the Great Plains, the Rocky Mountains and Great Basin, and along the Mexican boundary.

"Up to 1867," wrote Director Clarence King in his first annual report of the U. S. Geological Survey, "geology was made to act as a sort of camp follower to expeditions whose main object was topographical reconnaissance. . . . Eighteen hundred sixty-seven, therefore, marks, in the history of national geological work, a turning point, when the science ceased to be dragged in the dust of rapid exploration and took a commanding position in the professional work of the country."

Continued King: "Congress, even then, hardly more than placed the Federal work on a par with that prosecuted by several of the wealthier States. During the years when the Federal geologists were following the hurried and often painful marches of the Western explorers, many States inaugurated and brought to successful issue State surveys whose results are of dignity and value."

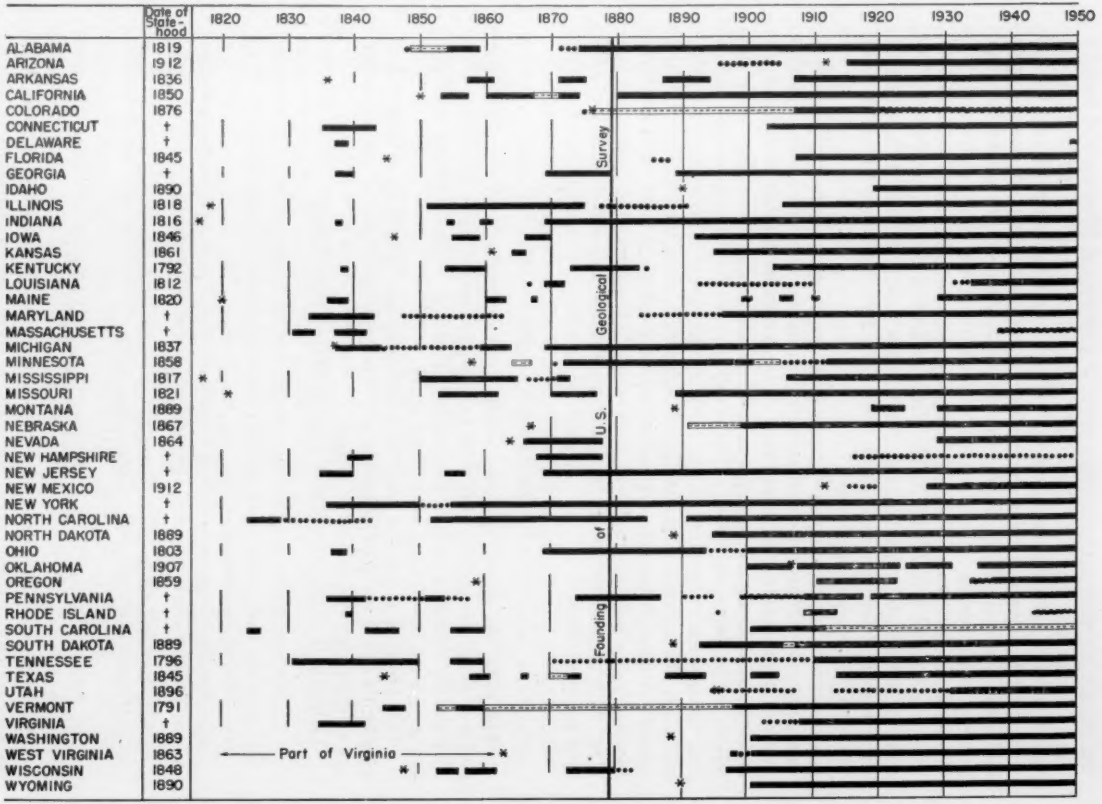
In 1867—the turning point in national geological work—Congress authorized the geological exploration of the fortieth parallel by King, geographical and geological survey of the Territories by Hayden, and geographical and geological survey of the Rocky Mountain Region by Powell. In 1879 these were consolidated by Congress into the United States Geological Survey.

Thus the Federal government after fifty years followed the suit of the states. There are obviously national interests as well as state interests to be served. Reports on the public domain, on regional problems, such as the mechanics of Appalachian structure or the clays of the United States east of the Mississippi River, on broad geological subjects such as the Paleozoic fishes of North America or the theory of metamorphism or analyses of rocks and minerals, and on strategic minerals of the nation, are indicative of the need for a national organization.

Since its founding the U. S. Geological Survey has played a large role in the advancement of the geological profession. It has developed specialists in geological subjects who have rendered important service to states, to various branches of the Federal government, and to science.

In the year that the U. S. Geological Survey was founded, only 10 state surveys of 38 states were active—Alabama, Indiana, Illinois, Kentucky, Michigan, New Jersey, New York, North Carolina, Ohio, and Texas. Illinois was active only in the sense that State Geologist Worthen was engaged in prepar-

Figure I. - CHRONOLOGY of STATE GEOLOGICAL SURVEYS



ing his last volume on the *Geology and Paleontology* of Illinois, field surveys having been discontinued in 1875. The surveys of Georgia, New Hampshire, and Wisconsin were discontinued in 1879. T. C. Chamberlin, R. D. Irving, and C. R. Van Hise came into the limelight as a result of their Wisconsin work and soon joined the U. S. Geological Survey. Among others who had had previous state survey experience were Clarence King, G. K. Gilbert, C. A. White, J. S. Newberry, Raphael Pumpelly, Leo Lesquereux, O. C. Marsh, Edw. Orton, and I. C. White. The State geological surveys continued to be a source of strength in the national effort by their fund of detailed information and by their financial cooperation. In 1950 they contributed in excess of $1,000,000 to cooperative funds.

In establishing the U. S. Geological Survey, it seems clear that Congress was simply expressing the sentiment of intelligent, forward-looking citizens that the nation would profit from now on by systematic studies of the geology and mineral resources of the country and by extending and supplementing the efforts of the individual states. The result has justified the innovation. Not only has the nation profited by the Geological Survey's execution of its programs but the activity of the states has increased. As shown in Figure 1, the number of state geological surveys has not only increased since 1890 but their continuity has been greater than ever before. Doubtless the public support given both the Federal survey and the state surveys is a reflection of the common public sentiment.

## SCIENCE AND THE ECONOMIC PATTERN.

The earth has always been the mother of mankind, and as the wants and needs of man have grown, this relationship has become more intimate. Science and the economic pattern are mutually reactive. The development of one has stimulated the development of the other.

This audience is familiar with the accelerated rate of change in recent decades and there is no need to review it. Virtually no aspect of our existence has escaped this revolutionary change.

However, I invite attention to two pertinent observations:

(1) Modern geological surveys should not bear any greater resemblance to the early state surveys than does the economic pattern of today to that of the early period.
(2) Geological surveys should command all the power of modern science to meet the needs of the present economic pattern.

These are offered as basic premises for the consideration not only of survey administrators but of the entire profession.

## GEOLOGICAL SURVEYS OF THE FUTURE.

Speaking as a state geologist, I trust that it is appropriate to express myself on the matter of state geological surveys of the future, particularly on the principles that should govern their character of organization, the scope of their programs, and policies of operation.

I feel inclined to do this because it is apparent that too many old traditions are being preserved by the states at the sacrifice of meeting the needs of the economic pattern which is ours to serve. Marcus Aurelius once said: "What is not good for the swarm is not good for the bee." A restatement of this might be: "What will help the human economy will help the organization serving it."

It is obvious that no two state geological surveys can be alike. The states all differ in their resources, their economic pattern, their ability to support a survey, their statutory requirements, their institutions, and their customs. These factors in any state provide the environment within which an organization must be oriented, its program determined, and its operations conducted.

Some things, however, are common to every state: (1) the need for geology to serve its industries, its agriculture, its commerce, and its institutions; (2) the availability of modern science to render this service; and (3) knowledge of the policies that are fundamental to fruitful operation and to good public relations.

Inasmuch as it is geological materials and geological conditions with which the human economy is in part concerned and inasmuch as all of the sciences must be marshalled in their study, the personnel of geological surveys, unlike university departments of geology, must include other scientists in addition to geologists. The name "geological survey" should be indicative of the field of study rather than of the personnel composing it.

Nature makes no such distinction between the sciences as we recognize for purposes of university organization and specialization. Therefore, the staff of a geological survey of necessity must include, in addition to specialists in geology, specialists in chemistry, physics and engineering. Furthermore, because we serve the existing economic pattern, there should be provision made for studies in mineral economics.

The geological surveys of the future should be intensive research institutions with laboratories designed for their special purposes. Laboratories of paleontology and petrography are admittedly fundamental but in these days of abundant access to subsurface information laboratories for the study and interpretation of well cuttings and diamond-drill cores are imperative as are also chemical, spectrographic and X-ray laboratories.

The time has passed when the world of technology could depend primarily on information gained from general geologic studies and from empirical engineering tests on samples. The discovery of additional resources requires geophysics and geochemistry. Furthermore, new fundamental information on the physical and chemical nature of materials, including their atomic structure, is required not only to discover additional metallic and petroliferous resources of great urgency but, in the field of industrial minerals, to discover what deposits are adaptable to meet precise specifications and to ascertain what processes of beneficiation are feasible and economic to convert the raw material into a usable product.

The survey organization must likewise maintain adequate technical files, a library of essential information, a clerical staff, help for operation of preparation rooms, mechanics for maintenance of a fleet of motor vehicles, and

machinists to design and construct research equipment not available on the open market.

We must lift our sights and recognize new values. A research and service organization of this type will be invaluable to all states in these highly competitive times. Businessmen of vision will lend their support to any such enterprise that is so constructive and helpful to the state's progress.

We see ahead an atomic age. As the changes which it will bring to our economic pattern become clearer we must adjust our programs and our *modus operandi* accordingly.

The administration of sound policies to govern public relationships deserves constant attention by directors and staff members. In addition to matters of integrity in protecting confidential records and in the proper use of information gained at public expense, the survey should insist upon its function as a research institution and avoid becoming a regulatory agency or a service agency, for routine analyses and other work at the sacrifice of research, and in competition with commercial laboratories.

Cooperative relationships should be sought with other organizations to cover inter-areas of research or problems requiring the attention of specialists not possessed by the survey.

State interests should predominate in determining state survey programs and national interests for Federal programs. Except under unusual circumstances the development and control of the resources of a state are the concern primarily of that state, and it is the better part of wisdom that the information concerning its resources should be in the files of the state organization for prompt and convenient reference.

The need for geological surveys of the type which is proposed here is greater than is commonly recognized and deserves careful consideration and action. The circumstances and necessities of the present economic pattern call for a widespread reorganization of existing state surveys into research institutions that will provide the scientific information required both for the present development of our natural resources and for the shaping of sound policies of conservation for the future.

ILLINOIS STATE GEOLOGICAL SURVEY,
URBANA, ILL.,
*April 9, 1951.*

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# CLASSIFICATION AND DEFINITIONS OF TEXTURES AND MINERAL STRUCTURES IN ORES.

G. M. SCHWARTZ.

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ABSTRACT.

The microscopic study of ores has been extensive during the past forty years, but a satisfactory classification and definition of textural terms has not been forthcoming. A preliminary list of textural terms taken from the literature and arranged in groups according to origin is given herewith. The terms are defined and brief comments added where desirable. References to publications where the terms are used are given for each to permit ready access to additional data on a given texture.


## INTRODUCTION.

THE intensive microscopic study of opaque ores started near the beginning of the present century. In the United States a few papers appeared previous to 1913 and in that year the publication of Singewald's papers on the titaniferous magnetites and Graton and Murdock's treatise on the sulphide ores of copper brought the significance of such studies into sharp focus. Since then parts, or all, of hundreds of articles, bulletins and books have been devoted to the microscopic description of opaque minerals. Growth of the subject has been rather haphazard and not much standardization has resulted. This is particularly true of the terms used for textures and mineral structures. In fact the situation seems precisely that stated by Cross, Idding, Pirsson and Washington for igneous rocks in 1906. They say, "The vagueness that characterizes descriptions and conceptions of textures of igneous rocks is due in part to a lack of systematic treatment of the subject by petrographers, and a consequent inexactness in the terminology by which definite conceptions may be expressed. It is also due to the intricacies of the textures to be described and to their diversity."

In describing ores, texture and structure have been used interchangeably and to some extent they are interchangeable. This is bound to be confusing. There have been few serious attempts to organize and define the terms used

for textures of ores and the writer does not know of a list that is complete. In American geology the term structure, when used without qualification, usually refers to the larger features of rocks including ores. Such features include bedding, joints, faults, folds, and so on. As a rule, these structures are not important in microscopic studies, although microscopic faults, folds and fractures have been observed.

Texture refers to the size, shape and arrangement of grains of one or more minerals which make up the ore or rock. In rocks the features that determine the texture are: crystallinity, granularity and fabric; however, ore minerals are rarely, if ever, amorphous so crystallinity is not a variable in ores.

Mineral structure properly refers to the internal features of a mineral grain or single crystal, for example zoning of a crystal. The term zone is not always used in this restricted sense, but is used for a feature confined to a single mineral such as spherulitic structure which may be an aggregate of a large number of minute needles. In malachite, for example, variation in color may give zoning at right angles to the needles. Spherulitic aggregates are not always confined to a single mineral, for example, alternating zones of chrysocolla and quartz. This is the mass texture of Edwards. These complexities emphasize the difficulty involved in any logical classification based on precise definitions. Edwards gets around the difficulty by referring to all arrangements between or in minerals of ores as textures and not using the term structure.

## COMMENTS ON PREVIOUS PUBLICATIONS.

The first general work to be published in English on the microscopic study of ore minerals was Van der Veen's Mineralography and Ore Deposition. The descriptive part covers only the native metals and a later volume was to follow but its preparation was prevented by the author's untimely death. Van der Veen does not offer any organization of textural terms, but he illustrates many of the common textures with a series of 130 excellent microphotographs. His index to figures includes the following textural terms: cellular, concentric, concentric shaly, curvi-planar, emulsion, eutectic, eutectoidic, feathery, plumose, granular, graphic, lattice, crystallographic, incipient lattice, network, pseudo-dendritic, recrystallization, scaly, and zonal. The usage of the terms texture and structure by Van der Veen is essentially that indicated by the definitions given above.

As far as known, the first paper to produce a classification of textures was published by Grigoriev (12) [1] in Russian with an English abstract. Texture and structure were used in the sense adopted in Russian and German. Texture refers to features discerned by the unaided eye and structure to the internal fabric visible under the microscope. Grigoriev's list included most of the structural (textural) terms in common usage and twenty-four drawings illustrate common examples. His genetic classification is as follows:

[1] Numbers in parentheses refer to Bibliography at end of paper.

I. Structures of deposition.
   1. Granular, 2. porphyritic, 3. graphic, 4. subgraphic, 5. zoned, 6. banded, 7. oolitic.
II. Structures of unmixing.
   1. Cell, 2. lattice, 3. emulsion, 4. graphic, 5. mottled.
III. Structures of replacement.
   1. Filiform, 2, cell, 3. shredded, 4. skeleton, 5. graphic, 6. lattice, 7. zoned, 8. dendritic, 9. cement.
IV. Metacolloid structures.
   1. Colloform, 2. perlitic, 3. spherulitic, 4. banded, 5. zoned, 6. gel.
V. Structures of pressure.
   1. Rumpled, 2. crushed, 3. banded, 4. granular.

The next important contribution to the general study of ores, in contrast to papers on specific problems or districts, is Schneiderhöhn and Ramdohr's monumental work, Lehrbuch der Erzmikroskopie, published in 1931. The great range of textures and mineral structures in ores are beautifully illustrated and most of the textures listed in the classification given below will be found among the 235 microphotographs.

Recently the Australasian Institute of Mining and Metallurgy has published a book entitled Textures of the Ore Minerals and Their Significance (1947) prepared by A. B. Edwards. The textures are illustrated by 131 excellent microphotographs. Edwards' compilation goes a long way to make available a systematic treatment of ore textures and it is unfortunate that it is not more readily available in the United States. The organization of Edwards' material, however, does not offer a classification of textures on a simple basis. For example, Chapter 1 is entitled "The texture of the native metals" and Chapter 2, "Primary zoning and banding in oxide and sulphide ores." The first chapter, as well as the second, therefore includes zoning or banding as the microphotographs show. This difficulty stimulated the writer to try to organize a simple classification.

When the manuscript for this paper was nearing completion, Bastin's memoir entitled, "Interpretation of ore textures" appeared containing many illustrations of textures and a particularly good discussion of the origin of textures. A few new terms were suggested by Bastin and these have been included in this tabulation.

## CLASSIFICATION.

Classification of textures and structures of ores and ore minerals is peculiarly difficult because of the great variation in textures and structures resulting from the complex processes involved in their origin and many textures form in more than one way. Another complication is the fact that various writers have used many different terms for similar, or essentially similar, textures. Also some terms are general, others specific in meaning; for example there are several kinds of crystallographic textures, such as triangular, lamellar, and lattice; oriented intergrowth texture is a term that seems essentially synonymous with crystallographic.

The classification as presented below includes practically all of the textural terms that have been used in papers published in English and either defined or illustrated sufficiently to permit a reasonably precise definition. No completely logical classification has seemed possible but the present arrangement is presented in the hope that a better one may be suggested. Meanwhile it should be useful to students in gaining a reasonable idea of the range of textures in ores and a somewhat precise definition of each.

It should be emphasized that in the classification primary and secondary are used purely in a textural sense and do not have the significance of hypogene and supergene.

The number of terms listed is large but does not necessarily cover every relationship found in the microscopic study of ores. The variations in ores, particularly those resulting from replacement, are so great that it seems unlikely that satisfactory terms can be suggested to cover every possibility. Rather than increase the number of terms, it seems best to depend on description where no textural term in current usage seems to fit, and for this reason new textural names are avoided in this paper. Most textures found in igneous rocks also occur in magmatic ores and it has not seemed necessary to include them unless they apply to other ores. Bastin (19, pp. 3–13), gives an excellent discussion of igneous rock textures found in magmatic ores.

LIST OF TEXTURES.

*Primary.*

1. Banded texture
2. Caries texture
3. Cement texture—replacement of cement by ore in minerals
4. Cockade or ring texture
5. Colloform, gel, or colloidal texture, Leisegang ring texture
6. Comb texture
7. Crystallographic texture
8. Dendritic, pseudodendritic, ice flower texture
9. Diabasic texture
10. Equigranular, granular, allotriomorphic, polyhedral or mosaic texture
11. Fibrous, feathery or plumose texture
12. Foliate texture
13. Granule texture—rounded grains, rounding is primary in origin.
14. Graphic, micrographic, myrmeketic, or pseudoeutectic texture, also subgraphic texture
15. Herringbone texture
16. Mottled texture
17. Mutual boundary texture
18. Oolitic, pisolitic, concretionary, concentric, scaly, pellet, framboidal texture
19. Porphyritic and porphyroblastic texture
20. Rosette texture
21. Spherulitic or radiating aggregate texture
22. Wire texture

*Secondary.*

1. Box work texture
2. Brecciated, "exploding-bomb" or crushed texture
3. Core or atoll texture, also tubercle texture
4. Filiform texture

5. Granulated mylonitic or microbrecciated texture
6. Ice-cake texture
7. Organic or cell texture
8. Relict texture
9. Rim texture, also reaction rim texture
10. Rumpled texture
11. Septarian texture, syneresis or shrinkage cracks texture
12. Serrate texture
13. Shredded texture or shred-like texture
14. Translation twinning texture
15. Veined and reticulate texture
16. Herringbone texture
17. Metacolloid or crackled texture

*Ex-solution Textures.*

1. Crystallographic or oriented intergrowth textures
   (a) Lattice, lamellar or Widmanstätten texture
   (b) Triangular texture
   (c) Seriate texture
2. Cell, cellular, net or mesh texture
3. Emulsion texture
4. Oleander-leaf texture
5. Pseudoeutectic or graphic texture
6. Eutectoid texture

*Mineral Structures.*

1. Cleavage structure
2. Herringbone structure
3. Lamellar twinning structure
4. Polysynthetic twinning structure
5. Zonal structure
6. Skeleton texture

## DEFINITIONS AND COMMENTS.

Following are definitions of each texture. Reference to the figures in this paper follow the name of the texture. Following the definitions are comments, where these seemed desirable, and finally a reference is given where the texture is used and usually illustrated.

### *Primary Textures.*

1. *Banded texture.* (Fig. 1.) Commonly a structure, especially when on a large scale. Alternating bands of varying minerals or varying color within a mineral. There are several kinds formed in different ways. Crustified banding, colloform banding, rhythmic banding are examples. Crustified banding develops in a fissure and may be symmetrical. Scalloped or colloform banding may result from colloidal deposition. Many minerals are involved including several sulphides. (18, pp. 17–18.)

2. *Caries texture.* Scallop-like contacts or smooth concave and convex boundaries. Abundant between many common minerals such as chalcopyrite, bornite, sphalerite, tetrahedrite, pyrrhotite. (16, p. 589; 18, p. 107.)

3. *Cement texture.* (Fig. 2.) Cementation or replacement of cement in a sandstone or conglomerate by ore minerals. (12, p. 55.)

4. *Cockade or ring texture.* Fragments of rocks or ore enclosed by successive crusts of other minerals. May resemble rosette texture. (18, p. 17; 19, p. 17 and Pl. 3.)

5. *Colloform, gel or colloidal texture.* (Fig. 3.) A series of concentric or scalloped layers with curvature convex toward the younger surface. Examples: chrysocolla, malachite, azurite, chalcedony, goethite, psilomelane, and many others. This texture is common in ores in which supergene processes have been active. Spherulitic, cockade and rosette textures are closely related. (19, p. 26) uses the term colloidal textures to cover the whole range of textures that may have formed by original deposition in a colloidal state. See Bastin, Memoir 45, chapters 3 and 4 for discussion of colloidal deposition and ore textures, also several pages and figures in Edwards.

6. *Comb texture.* Individual crystals with long axes normal to walls of a vein. Quartz most common example. (18, p. 17; 19, p. 15.)

7. *Crystallographic texture.* (Fig. 4.) The crystallographic planes of the host mineral control the distribution of inclusions or veinlets. Forms by replacement and especially by ex-solution. Many types such as lamellar, triangular, etc. come under this general heading. (10, p. 56.)

8. *Dendritic, pseudodentritic or ice flower texture.* (Fig. 5.) Minerals with branching tree-like form. Van der Veen uses pseudodendritic apparently because many form by replacement rather than as free growth such as, manganese oxide on rock surfaces. This qualification does not seem necessary for a texture. Examples: Native silver in carbonate, also various arsenides and some sulphides in carbonate. Van der Veen, several pages and figures.

9. *Diabasic texture.* (Fig. 6.) Diabase containing ore minerals enclosing feldspar in place of pyroxene. (11, p. 261.)

10. *Equigranular, granular, allotriomorphic, polyhedral or mosaic texture.* (Fig. 7.) Essentially the same as granitoid in igneous rock, but no relation to size and the grains lack crystal faces. (10, p. 56; 5, p. 37; 18, p. 111.)

11. *Fibrous, feathery or plumose texture.* Elongated blades with serrated or fibrous edges, resembling a feather or plume. Examples: arsenic, wurtzite, covellite. (10, Figs. 28, 59.)

12. *Foliate texture.* (Fig. 8.) Platy minerals in parallel arrangement.

13. *Granule texture.* (Fig. 9.) Literally granule means a small grain. Generally oval or rounded grains in a matrix but grains are not of clastic origin and lack internal structure. Used especially for the round or oval grains in iron formation. (1, Plate IX.) The false oolites of Cayeux much resemble granule texture of Lake Superior ores. (19, Pl. 17, Fig. 4.)

14. *Graphic, micrographic, myrmeketic or pseudoeutectic texture; also subgraphic texture.* (Figs. 10 and 11.) Curved lamellar intergrowths resembling some eutectic intergrowths found in metal alloys. In graphic granite partial crystallographic control makes a pattern suggesting cuneiform or runic characters. The textures included are highly complex and have been described as twisting tongues of the sulphides with smooth contacts and the embayments and tongues turn sharply to form hooks. Sub-graphic is used for poorly developed examples more or less resembling typical graphic intergrowths. Myrmeketic suggests the worm-like nature of some examples. The textures are considered by various authors to originate by simultaneous deposition, by unmixing and by replacement. True eutectics are probably rare or lacking in ores. (10, p. 56; 13, p. 137; 8, p. 24.)

15. *Herringbone texture.* (Fig. 32.) Long narrow spine with more or less symmetrically arranged zones or spines on each side. Related to dendritic and skeleton textures, and may resemble feathery or plumose textures. May also occur as a structure within grains. Forms by replacement and during primary crystallization. Examples: Native silver, native copper, ilmenite in sinter. (18, pp. 4 and 7.)

16. *Mottled texture.* Somewhat indefinite aggregate of two types of chalcocite, usually referred to as blue and white chalcocite. Edwards uses the term for an ex-solution texture similar to emulsion texture. (18, p. 80; 12, p. 53.)

17. *Mutual boundary texture.* Two or more minerals whose contacts are smooth regular curves that show no projections from one mineral into the other. May also be secondary. (13, p. 160.)

PRIMARY TEXTURES.

FIG. 1. Banded texture. Galena-sphalerite ore, Sullivan Mine, B. C. Natural size.

FIG. 2. Cement texture. Sand grains cemented by galena, Cole's Mine, Colo. × 50.

FIG. 3. Colloform or gel texture. Malachite and quartz alternating. Locality? × 20.

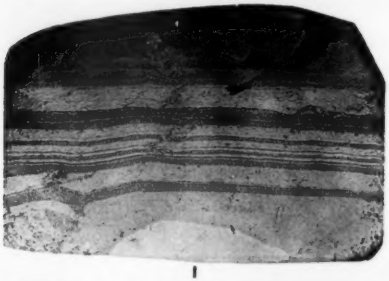
FIG. 4. Crystallographic texture. Ilmenite oriented along octohedral planes of magnetite. Pillsbury Lake, Minn. × 100.

FIG. 5. Dendritic texture. Argentite dendritic forms in galena (etched black). Silver Islet, Lake Superior. × 225.

FIG. 6. Diabasic texture. Pyrrhotite and chalcopyrite (black) as matrix to euhedral plagioclase of an olivine diabase. Grand Portage area, Minn. × 18.

FIG. 7. Equigranular, granular or allotriomorphic texture. Quartz and hematite, Cuyuna iron-bearing district, Minn. × 100.

FIG. 8. Foliate texture in specular hematite, Utah. × 80.



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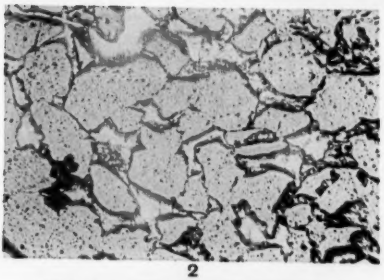

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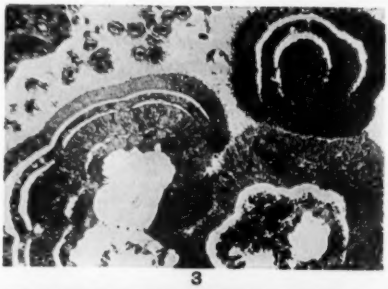

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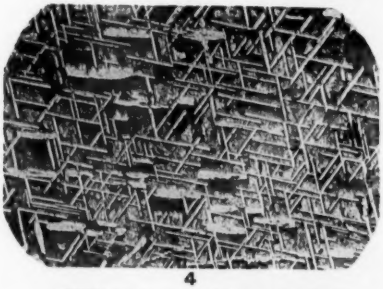

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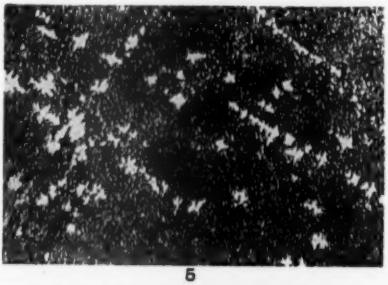

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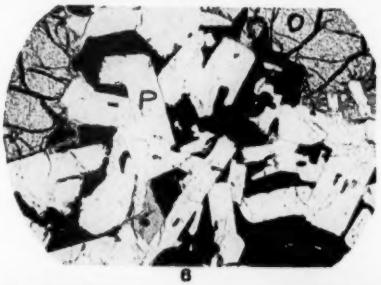


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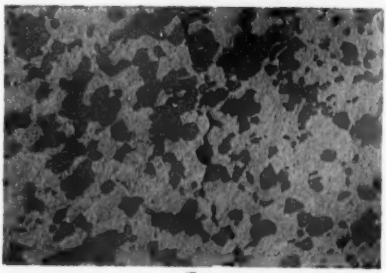

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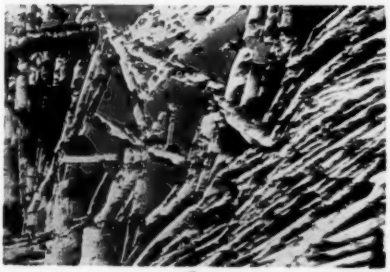

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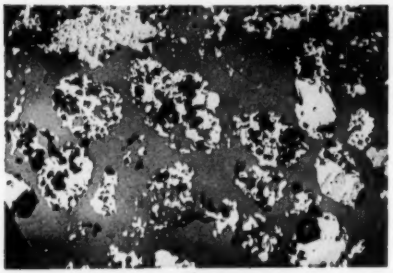

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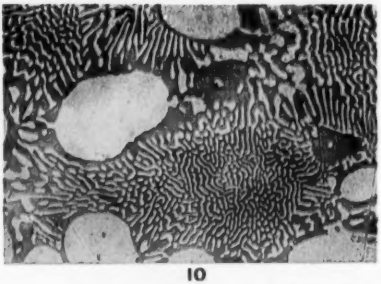

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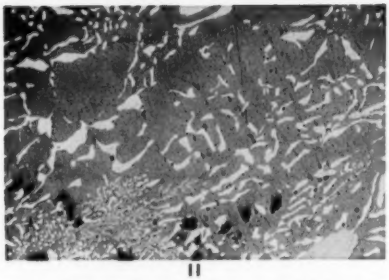

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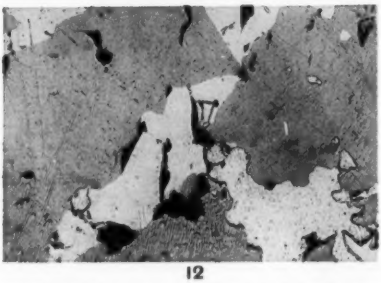

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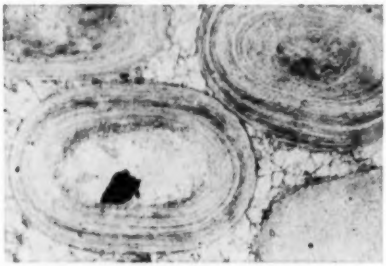

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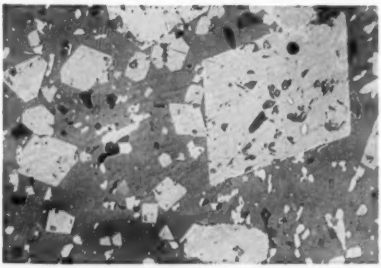

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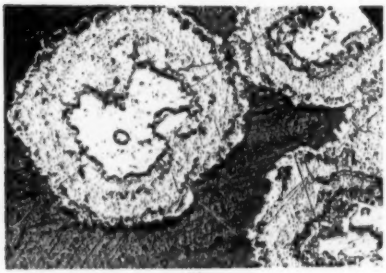

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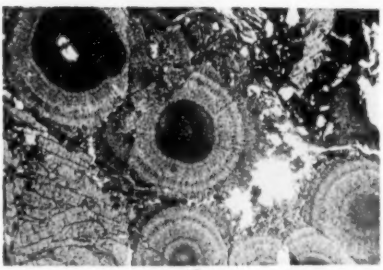

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FIG. 9. Granule texture. Granules of magnetite in quartz. East Mesabi district, Minn. × 67.

FIG. 10. Graphic or myrmeketic texture. Domeykite in metallic copper. Synthetic.

FIG. 11. Subgraphic texture. Galena in bornite. Butte and Superior Mine, Mont. × 232.

FIG. 12. Mutual boundary texture. Pyrrhotite and sphalerite. Sullivan Mine, B. C. × 80.

FIG. 13. Oolitic texture. Iron ore, Cleveland district, England. Thin section. × 73.

FIG. 14. Porphyroblastic texture. Magnetite crystals embedded in jasper. Nemo area, Black Hills, S. D. × 100.

FIG. 15. Rosette texture. Rosettes of arsenides with a core of native silver, breithauptite and nicollite. Cobalt, Ont. × 45.

FIG. 16. Spherulitic texture. Spherulites of malachite in copper oxide ore. Ajo, Ariz. × 17.

SECONDARY TEXTURES

FIG. 17. Boxwork texture. Limonite boxwork with remnants of cuprite. Bisbee, Ariz. × 50.

FIG. 18. Brecciated or "exploding bomb" texture. Chalcopyrite fragments in carbonate, Iron Cap Mine, Globe, Ariz. × 50.

FIG. 19. Core or atoll texture. Chalcopyrite in bornite. Susie Island, Lake Superior. × 100.

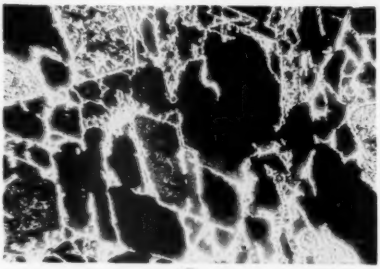
FIG. 20. Granulated, mylonitic or microbreccia texture. Bornite and chalcopyrite in gangue. Butte, Mont. × 535.

FIG. 21. Ice-cake texture. Pyrite partly replaced by chalcocite. Old Dominion Mine, Globe, Ariz. × 100.

FIG. 22. Organic or cell texture. Chalcocite replacement of wood. × 15.

FIG. 23. Relict texture. Remnants of magnetite in a grain largely replaced by hematite. San Manuel area, Ariz. × 340.

FIG. 24. Rim texture. Rims of hematite around magnetite grains. Iron ore sinter. Reading Iron Company. × 300.



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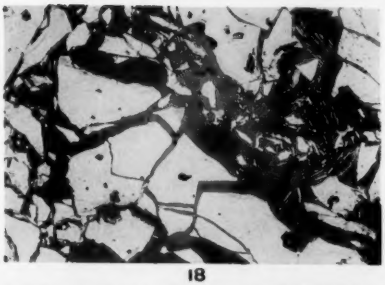

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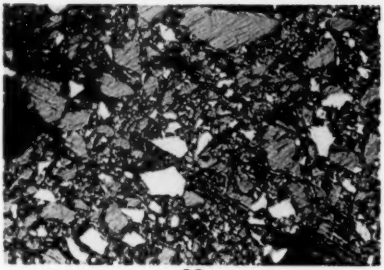

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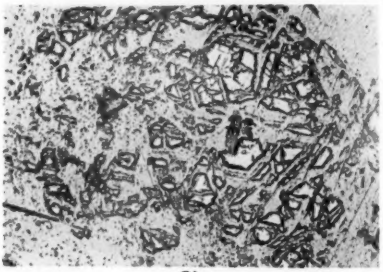

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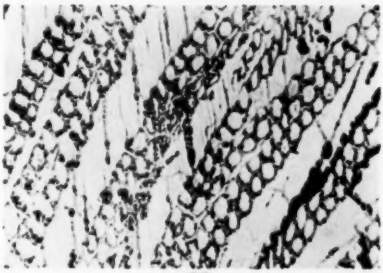

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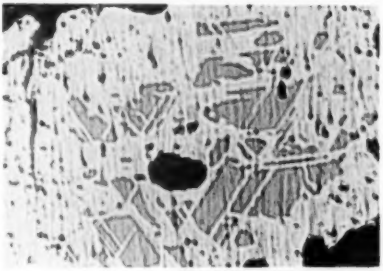

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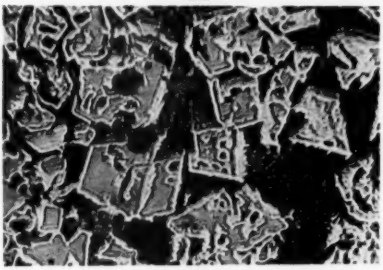

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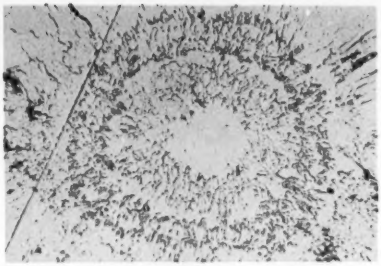

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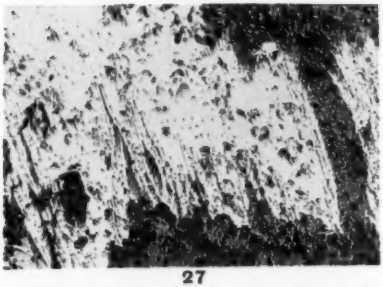

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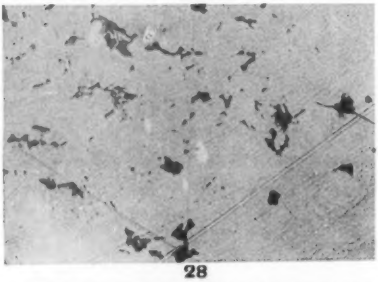

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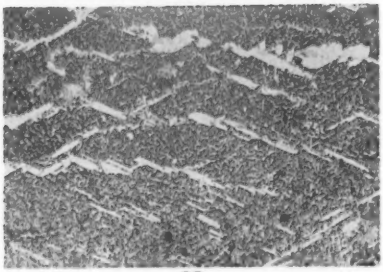

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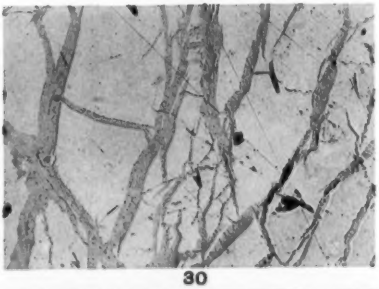

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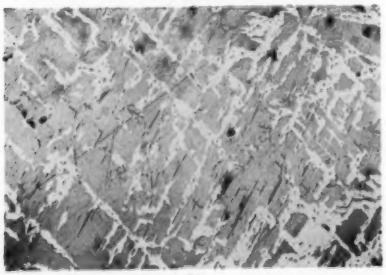

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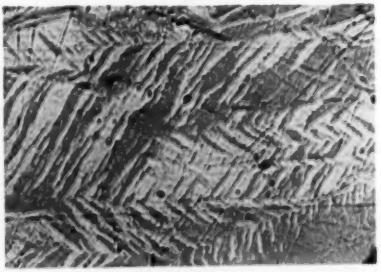

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FIG. 25. Rumpled texture. Hematite. Lake Wahwandin, Quebec. × 21.

FIG. 26. Septarian texture. Chalcocite. Butte, Mont. × 125.

FIG. 27. Serrate texture. Pyrrhotite penetrated by gangue and pyrite forming a serrate boundary. Santa Eulalia, Mexico. × 150.

FIG. 28. Shred-like texture. Bornite shreds in chalcocite. Butte, Mont. × 250.

FIG. 29. Translation twinning texture. Ilmenite in magnetite (etched). Sept Isle, Quebec. × 100.

FIG. 30. Veined texture. Chalcopyrite cut by veinlets of chalcocite. Campbell Mine, Bisbee, Ariz. × 80.

FIG. 31. Reticulate texture. Bornite replaced along cleavage by a network of chalcocite. Belmont Mine, Butte, Mont. × 100.

FIG. 32. Herringbone texture. Chalcopyrite replaced by bornite that developed herringbone texture. Susie Island, Lake Superior. × 50.

EX-SOLUTION TEXTURES.

FIG. 33. Lattice, lamellar or Widmanstätten texture. Chalcocite blades with bornite. Leonard Mine, Butte, Mont. × 800.

FIG. 34. Triangular texture. Ilmenite in magnetite (etched). Tucker Lake, Minn. × 100.

FIG. 35. Seriate texture. Ilmenite plates of two sizes in magnetite (etched). Duluth gabbro, Cook County, Minn. × 100.

FIG. 36. Cell, net, or mesh texture. Sphalerite with pyrrhotite forming network along grain boundaries. Cowboy Mine, Takelma, Wash. × 100.

FIG. 37. Emulsion texture. Allemontite. Arsenic in antimony. Allemont, France. × 200.

FIG. 38. Oleander-leaf texture. Bornite inclusions in chalcocite. Susie Island, Lake Superior. × 800.

FIG. 39. Pseudoeutectic or graphic texture, possibly eutectoid. Allemontite, Allemont, France. (After Van der Veen.) × 85.

FIG. 40. Eutectoid texture. Chalcocite and bornite. Mufulira Mine, Southern Rhodesia. × 700.

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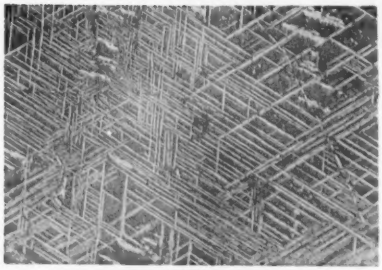

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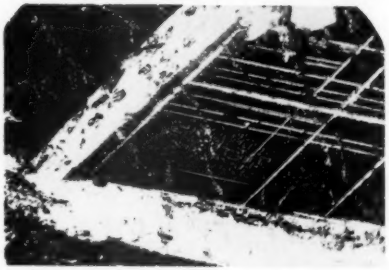

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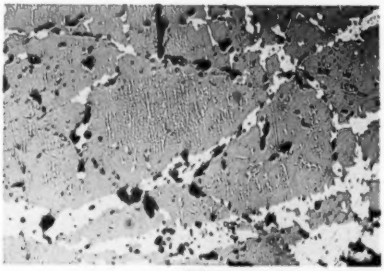

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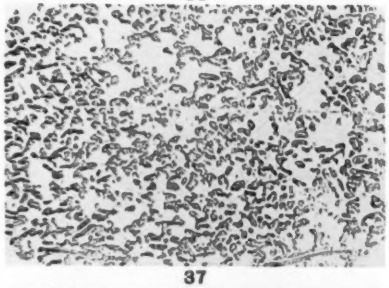

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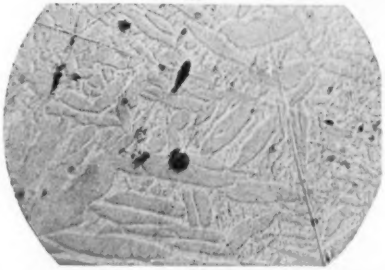

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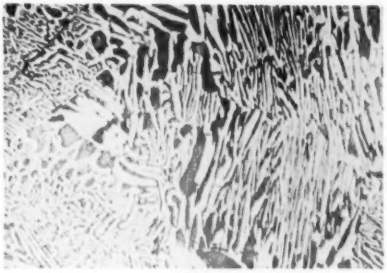

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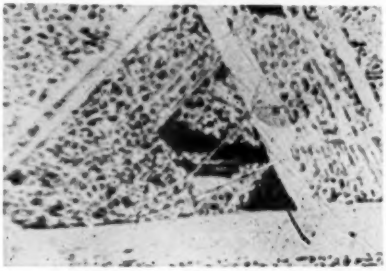

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18. *Oolitic, pisolitic, concretionary, concentric, pellet, framboidal and scaly texture.* (Fig. 13.) There is great variety in these textures, but they are characterized by concentric shells of slightly varying properties normally as a result of variation during growth. Closely related to banded, gel and colloform textures. Examples: Goethite, hematite, psilomelane, chrysocolla, malachite, and many others. Edwards, various pages. Pellet texture is suggested by Bastin (19) for minute pellets either of colloidal or replacement origin and closely resembling oolites. Framboidal texture is used for pellets forming aggregates resembling the fruit of a raspberry. (19, p. 30.)

19. *Porphyritic or porphyroblastic texture.* (Fig. 14.) Euhedral crystals in a matrix of other minerals lacking in crystal outlines. Grains of matrix usually smaller, but not necessarily so. Not often used for ores, but there is no suitable substitute. Examples: Pyrite, arsenopyrite, magnetite most common.

20. *Rosette texture.* (Fig. 15.) Rounded, somewhat scalloped aggregates of one or more minerals. (8, p. 20.)

21. *Spherulitic or radiating aggregate texture.* (Fig. 16.) Groups of fibers, radiating from a central point or area, and these units embedded in a groundmass. (12, p. 55.)

22. *Wire texture.* Perhaps more properly a structure. Wire-like forms of native metals are common. Often the core is granular and the outer zone is rind-like. Examples: Native copper, native silver, native gold, etc. (18, p. 7.)

### *Secondary Textures.*

1. *Box work texture.* (Fig. 17.) A porous aggregate with plates or septa which intersect at various angles leaving open, box-like spaces.

2. *Brecciated "exploding bomb" or crushed texture.* (Fig. 18.) Fragmented without notable rounding, displacement often not great. Very common texture especially pyrite broken and cemented by later minerals. (5, p. 37.)

3. *Core or atoll texture.* (Fig. 19.) In core texture a second mineral occurs on the inside of an area of another. Not common but good examples known. Pyrite-galena, pyrite-sphalerite, pyrite-chalcopyrite, galena-anglesite. Where the residual rim is enclosed in the same mineral, the term atoll texture has been used. (18, p. 97.) Bastin (19) uses tubercle texture for somewhat similar, but often complex arrangements, of ore minerals in calcite gangue.

4. *Filiform texture.* Thread-like forms embedded in another mineral. Much the same as wire texture. (12, Fig. 10.)

5. *Granulated, mylonitic or microbrecciated texture.* (Fig. 20.) Used for very finely broken ore minerals. Many minerals, particularly those that are brittle, are often minutely fractured.

6. *"Ice-cake" texture.* (Fig. 21.) Rounded and corroded remnants in a later mineral. Pyrite in chalcocite a common example. (6, Fig. 13.)

7. *Organic or cell texture.* (Fig. 22.) Replacement of organic forms especially cell walls by ore minerals. (16, p. 575.)

8. *Relict texture.* (Fig. 23.) Traces of original texture or structure as a result of pseudomorphous replacement such as cleavage or parting; also fragments of a mineral left behind by replacement of the main part. (18, p. 99.)

9. *Rim texture; also reaction rim texture.* (Fig. 24.) Narrow rims of secondary mineral around host. Mineral around either individual grains or along contacts between unlike minerals. (18, pp. 83, 96.) Examples: Bornite-chalcocite, magnetite-hematite, pyrite-chalcocite, pyrite-chalcopyrite. Reaction rims occur in igneous rock including magmatic ores. (19, p. 10.)

10. *Rumpled texture.* (Fig. 25.) Folded or rumpled minerals often with platy forms such as a specularite. (12, p. 56.)

11. *Septarian texture.* (Fig. 26.) *Syneresis or shrinkage crack texture.* A concretionary nodule intersected within by cracks often filled with a later mineral. (9, p. 123.) Syneresis or shrinkage cracks are terms used by Bastin (19) for a variety of minute fractures such as occur in colloidal ores.

12. *Serrate texture.* (Fig. 27.) Notched or toothed contacts or saw-toothed effect between minerals, usually a result of replacement. Colony (13) used terms jagged structure and penetrating structure for similar relations.

13. *Shredded or shred-like texture.* (Fig. 28.) Irregular particles of a mineral enclosed in another. May be replaced remnants or shreds, possibly also simultaneous inclusions such as bornite in chalcocite. (12, p. 54.)

14. *Translation twinning texture.* (Fig. 29.) Slip movement on adjacent twin planes. Equivalent of false cleavage. (18, p. 32.)

15. *Veined or reticulate texture.* (Figs. 30 and 31.) Veined texture is most common of all ore textures. Varies greatly in extent and form. Called reticulate texture where veins follow cleavage or parting nearly at right angles forming a net, for example bornite-chalcocite. (13, p. 144.)

16. *Herringbone texture.* (Fig. 32.) Rows of parallel patterns, which in any two successive rows slope in reverse directions. May also be a primary texture or structure. (18, pp. 4, 7.)

17. *Metacolloid or crackled texture.* Concentric texture in which minute cracks have developed by shrinkage during crystallization of the original colloid. (6, p. 412; 19, Pl. 6.)

### *Ex-solution Textures.*

1. *Crystallographic or oriented intergrowth textures.* Any texture in which the crystallographic properties of the host mineral control the texture. May be formed by replacement as well as by ex-solution.

(a) *Lattice, lamellar or Widmanstätten texture.* (Fig. 33.) Lath-shaped grains oriented along crystallographic directions in a crystal or grain of another mineral. Commonly a result of ex-solution; also, a similar texture may form by replacement. Examples: Magnetite-ilmenite, bornite-chalcocite, etc. Van der Veen, several pages and figures. (17, pp. 739–763; 18, Fig. 52.)

(b) *Triangular texture.* (Fig. 34.) Applied to ex-solution texture where the exsolved mineral is oriented along octahedral planes forming a diagrammatic triangular arrangement. Examples: Magnetite-ilmenite, magnetite-hematite, bornite-chalcocite, chalcopyrite-cubanite, and others. Also a replacement texture. (17, p. 751.)

(c) *Seriate texture.* (Fig. 35.) Arranged in a series. The size of the guest mineral varies with age or order of formations. (18, pp. 59, 80 and Figs. 61 and 62.)

2. *Cell, cellular, net or mesh texture.* (Fig. 36.) These textures may originate by segregation to grain boundaries on ex-solution. Similar textures may form by replacement. (10, p. 56; 12, Fig. 6.)

3. *Emulsion texture.* (Fig. 37.) Minute blebs or rounded inclusions of one mineral, irregularly distributed in another mineral. Examples: Sphalerite-chalcopyrite, stannite-chalcopyrite. (10, p. 46.) A similar texture may occur in calcite, as for example chalcocite inclusions in calcite from Susie Island, Lake Superior.

4. *Oleander-leaf texture.* (Fig. 38.) Inclusion of oleander leaf-shaped (spindle shaped) grains in a matrix. Probably rudely crystallographic. (7, p. 310 and Pl. 13, Fig. B.)

5. *Pseudoeutectic or graphic texture.* (Fig. 39.) Also called graphic etc. May be applied to pairs of minerals with graphic or myrmeketic texture resulting from ex-solution. (18, p. 102; 10.)

6. *Eutectoid texture.* (Fig. 40.) A graphic texture with each grain showing the complicated graphic intergrowth. Van der Veen. Several pages and figures. (18, p. 103; 10, Figs. 64–67.)

*Mineral Structures.*

These are forms within a single grain or crystal of a mineral.

1. *Cleavage structure.* Structure resulting from mineral cleavage.
2. *Herringbone structure.* Long narrow spines with symmetrically arranged arms. May occur within grains as a structure. (18, pp. 4, 7.)
3. *Lamellar twinning.* Twinning parallel to crystal planes within grains or crystals. Examples: Sphalerite, chalcopyrite, galena, etc. (10, p. 38 and Fig. 55.)
4. *Polysynthetic twinning.* In metallic minerals is essentially the same as lamellar twinning. (10, p. 38 and Figs. 29, 63.)
5. *Zonal structure.* Zonal growth of crystals or grains involving slight difference in composition or properties. Examples: Native metals, magnetite, galena, tetrahedrite, proustite, sphalerite. Edwards, several figures. (10, pp. 37, 43, 49 and Figs. 24–26 and 56–57.)
6. *Skeleton structure.* Crystal outlines incompletely filled with the mineral. Examples are sphalerite in chalcopyrite, magnetite in basalt and in synthetic sinters and slags. (14, p. 597.)

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# METALLOGENIC EPOCHS IN IDAHO.

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ABSTRACT.

Instead of two metallogenic epochs, a late Mesozoic and a mid-Tertiary, Idaho appears to have no less than five; namely, (1) late Precambrian, (2) early Tertiary, (3) mid-Tertiary, (4) late Tertiary, and (5) Quaternary. The role of the Idaho batholith (late Mesozoic) as the most important "mineralizer" in the State is discredited. Ore deposits supposed to be related to it genetically appear to have had their source in the more basic crust beneath the batholith and to have been associated with igneous activity that came near the end of the Laramide orogeny in early Tertiary time.

All the metallogenic epochs, except perhaps the last, are closely associated with igneous activity; the late Precambrian with basic sills and flows; the early Tertiary with hypabyssal porphyritic and non-porphyritic intrusives ranging from diabase and diorite to rhyolite porphyry and lamprophyre; the mid-Tertiary with granite and related porphyries from dacite to rhyolite, and lamprophyre; the late Tertiary with basaltic and rhyolitic flows; and the Quaternary with possible igneous activity manifested in hot spring action. The close association of the ores with lamprophyre dikes during the early and mid-Tertiary epochs invites speculation as to the origin of lamprophyres and their role in metallization.

## INTRODUCTION.

THE existence of two general groups of ore deposits in the State of Idaho has long been recognized; one is older than the Challis volcanics (Oligocene) and the other younger. The Challis volcanics has thus served as a useful datum in differentiating between two metallogenic epochs, the older and more important of which has been assigned to the late Mesozoic with the source of the ores in the Idaho batholith and the younger, to the Tertiary with the source in mid-Tertiary magmas.[1]

For some time the writer has had reason to doubt the genetic association of the early group of deposits with the Idaho batholith and has felt that the batholith has been given credit for deeds that it never performed and therefore has received a distinction to which it is not entitled. The writer has noted in particular that the supposedly related deposits possess features wholly incompatible with an assumed source in the batholith and that they show a much closer association with structural features of Laramide age and with igneous activity that occurred near the close of that orogeny than with any structural features and processes attributable to the batholith.[2] A review of the Tertiary

[1] Ross, C. P., The ore deposits of Idaho in relation to structural and historical geology: *in* Ore Deposits of the Western States (Lindgren Volume), Am. Inst. Min. Met Eng., pp. 265–270, 1933; A classification of the lode deposits of south-central Idaho: ECON. GEOL., vol. 26, pp. 169–185, 1931.

[2] Anderson, A. L., Role of the Idaho batholith during the Laramide orogeny: ECON. GEOL., vol. 43, pp. 84–99, 1948.

metallization has also brought out certain discrepancies in the age relations of the various deposits assigned to that metallogenic epoch. For example, there are some deposits, which, although younger than the Challis volcanics, are older than flows of Columbia River basalt and beds of the Payette formation (middle or upper Miocene), whereas there are other deposits which appear to be younger than the Columbia River basalt and a still younger succession of rhyolitic rocks of late Miocene or early Pliocene age, yet older than the beds of the Idaho formation (Pliocene and Pleistocene). Then there are a few deposits which, indirectly, appear to be younger than the Idaho formation. However, the story is not yet complete, for some mineralization may be traced back to late Precambrian time. Consequently, instead of two epochs of metallization, there appear to be no less than five, which for convenience may be listed as (1) late Precambrian, (2) early Tertiary, (3) mid-Tertiary, (4) late Tertiary, and (5) Quaternary.

The intent of this paper is to present the basic facts that justify the increase in the number of metallogenic epochs and at the same time show that the Idaho batholith has an undeserved reputation as an "ore mineralizer." The various epochs that are recognized are certainly not of equal rank or importance and the number may increase, if Mesozoic or possibly late Paleozoic epochs should eventually be recognized. Each of the metallogenic epochs, except the last, shows a marked association with igneous activity, and in the case of two of the epochs, the early and mid-Tertiary, a particularly close association with lamprophyres.

## PRECAMBRIAN EPOCH.

The Precambrian metallization is associated with the Purcell sills which intrude the Belt strata (Algonkian) near the Canadian border and may also be manifested in the copper deposits that are confined to the late Precambrian tillite and volcanic formation near Pocatello in the southeastern part of the State. The metallization associated with the Purcell sills is a basal magmatic segregation of disseminated pyrrhotite, pentlandite, gersdorffite, and chalcopyrite.[3] Appreciable amounts of such ore minerals have so far been found in only one of the sills, which locally has the composition of a uralite diorite (probably originally a gabbro). The sills are known to have been intruded in late Precambrian time and the ore in them must also be late Precambrian. The resemblance of this metallization to that at Sudbury, Ontario, is worthy of note.

The copper deposits near Pocatello occur along fractures in sheared tillites and other sedimentary rocks which were once interpreted as conglomerates of Ordovician age[4] but which more recently have been recognized as members of a late Precambrian glacial formation with intercalated volcanics.[5] The ore

[3] Kiilsgaard, T. H., Description of some ore deposits and their relationships to the Purcell sills, Boundary County, Idaho: Idaho Bur. Mines and Geology Pamph. 85, pp. 10–11, 1949.

[4] Weeks, F. B., and Heikes, V. C., Notes on the Fort Hall mining district, Idaho: U. S. Geol. Survey Bull. 340, p. 179, 1907.

[5] Ludlum, J. C., Precambrian formation at Pocatello, Idaho: Jour. Geology, vol. 40, pp. 81–95, 1942.

consists of bornite, chalcopyrite, and chalcocite, with chlorite, and is unlike any other ore in the region. The metallization is confined exclusively to the Precambrian rocks and, because of its restricted distribution, is thought to be Precambrian.

EARLY TERTIARY EPOCH.

The early Tertiary metallization constitutes what Ross [6] has previously defined as Mesozoic and which he believes has its source in the Idaho batholith and related intrusives. The deposits consist of precious-metal veins formed within the batholith and its outliers and lead-silver and other base-metal lodes in shear zones generally outside the batholith.

*Status of the Idaho Batholith.*

As the Idaho batholith has so long been looked upon as the most important "mineralizer" in the State, it is desirable that the batholith itself should be considered to ascertain if it is properly constituted to serve as the parent of the host of ore deposits that occur in and around it. In another report the writer [7] points out that the batholith was not emplaced as a unit but is the product of three separate emplacements, two of which took place during the later stages of the Sierra Nevadan orogeny, the earliest while stress action associated with the orogeny was still rather intense, the second after the stress had greatly lessened, and the third during the Laramide orogeny. The first two have characteristics of deep-seated emplacements, the last somewhat less so. Each emplacement was closed with formation of related aplites and pegmatites. The related (?) ore deposits are known to be younger than the latest emplacement (late Cretaceous) and thus are considerably younger than the two emplacements associated with the Sierra Nevadan orogeny (late Jurassic or early Cretaceous).

*Relations of the "Associated" Ore Deposits to the Idaho Batholith.*

The ore deposits "related" to the Idaho batholith are the most important in the State and include the productive lead-silver-zinc deposits of the Wood River and Coeur d'Alene districts, the antimony deposits in the Yellow Pine district, the copper-cobalt deposits in the Blackbird district, and the tungsten deposits in the Blue Wing district as well as deposits of the same or other metals in districts at present of less economic interest. The more pertinent relations of the ore deposits in these various districts will next be considered, particularly with respect to the rocks with which the ores are most closely associated.

*Wood River Region.*—As the ore deposits of the Wood River region were among the first to be accorded a source in the Idaho batholith,[8] a source also

[6] Ross, C. P., op. cit., Ore Deposits of the Western States (Lindgren Volume), pp. 265–270; op. cit., ECON. GEOL., pp. 169–185.

[7] Anderson, A. L., Multiple emplacement of the Idaho batholith: in preparation.

[8] Lindgren, Waldemar, Gold and silver veins of Silver City, De Lamar, and other mining districts in Idaho: U. S. Geol. Survey Twentieth Ann. Rept., pt. 3, pp. 190–231, 1900.

accepted by later writers,[9] and as the deposits have since been used as a basis for correlating similar deposits in nearby [10] and more distant areas [11] with the batholith, their relations are particularly significant. Fortunately the writer has recently had occasion to conduct studies in the region [12] and has had the opportunity to revaluate the genetic associations. The next several paragraphs are largely based on the writer's personal observations.

The granitic bodies of the area are recognized as belonging to the younger rock of the Idaho batholith and include a sill-like body of pyroxene-hornblende-biotite diorite, which intrudes faulted Carboniferous strata and which is itself intruded by quartz monzonite, long regarded as an outlier or part of the Idaho batholith. Associated with the quartz monzonite are numerous bodies of aplite and pegmatite, which also penetrate the diorite. Cutting all these are scattered porphyritic andesitic and dacitic dikes and locally many lamprophyric dikes.

The ore deposits occur as replacements along well defined fissure and fracture zones in the diorite, quartz monzonite, and adjacent Paleozoic sedimentary rocks, and, although in and near the granitic rocks, show a much more intimate association with the porphyritic andesites and dacites and particularly with the lamprophyres than with the quartz monzonite and related rocks. The sequence of events has been summarized by Hewett [13] as follows:

1. Intrusion of diorite.
2. Intrusion of granite (quartz monzonite) and pegmatites.
3. Intrusion of andesite and lamprophyric dikes.
4. Deposition of ores.

The intrusion of the porphyritic dikes has in large part been controlled by fractures independent of structures that directed emplacement of the diorite, quartz monzonite, aplite, and pegmatite. The widely scattered andesitic and dacitic dikes are in places cut and altered by the ore deposits, but the lamprophyric dikes, which show some petrographic resemblance to the porphyritic dikes, have a much closer association with the ores and are particularly numerous in underground workings where they may be observed to lie in and across the ore bodies. Some of the lamprophyric dikes, which are olivine-bearing varieties, have been somewhat altered by the mineralizing fluids, but some are little altered and are clearly younger than the ore.

These porphyritic and lamprophyric dikes were obviously intruded into cold rocks and at depths much less than those at which the diorite, quartz

[9] Umpleby, J. B., Westgate, L. G., and Ross, C. P., Geology and ore deposits of the Wood River region, Idaho: U. S. Geol. Survey Bull. 814, pp. 120–122, 1930.

[10] Ross, C. P., Geology and ore deposits of the Bayhorse region, Custer County, Idaho: U. S. Geol. Survey Bull. 877, pp. 101–102, 1937.

[11] Umpleby, J. B., and Jones, E. L., Jr., Geology and ore deposits of Shoshone County, Idaho: U. S. Geology Bull. 732, pp. 141–145, 1923. Ransome, F. L., and Calkins, F. C., The geology and ore deposits of the Coeur d'Alene district, Idaho: U. S. Geol. Survey Prof. Paper 62, pp. 134–140, 1908.

[12] Anderson, A. L., Geology and ore deposits of the Hailey-Bellevue mineral belt: Idaho Bur. Mines and Geology Pamph. 90, pp. 1–37, 1950.

[13] Hewett, D. F., Geology of the Minnie Moore and nearby mines, Mineral Hill mining district, Blaine County, Idaho: U. S. Geol. Survey Bull. 814, p. 219, 1930.

monzonite, and associated aplites and pegmatites were emplaced. Their intrusion and the closely accompanying mineralization therefore must have taken place considerably after the emplacement of the granitic rocks and their differentiates (late Cretaceous) but before the extrusion of the Challis volcanics which extend as a blanket across a part of the area and are not cut by any of the deposits. The prophyritic intrusives therefore must represent a local manifestation of the widespread igneous activity that occurred throughout much of the Rocky Mountain region at the close of the Laramide orogeny in early Tertiary time. Consequently, the associated ore deposits must have had their roots in the magma that fed the early Tertiary intrusives and not in the older magma of the batholith. The deposits thus must belong to the early Tertiary metallogenic epoch.

Similar deposits in the Little Wood River (Muldoon) district a few miles to the east are associated with dikes and a small stock of quartz monzonite porphyry whose textural and structural characteristics indicate consolidation much closer to the surface than when the Idaho batholith was emplaced. As the ore is pre-Challis, it, like the intrusives, must be a product of early Tertiary igneous activity.[14]

There are some "contact metamorphic" replacements in calcareous strata in the Wood River region, some along or close to granitic contacts, others not, which are reported to have been formed by emanations from the Idaho batholith.[15] The writer has examined some of these deposits and has concluded that they are structurally rather than genetically controlled and that the source of the ores is early Tertiary magma rather than the Idaho batholith.

As for the gold-quartz veins in the granitic rocks of the Hailey gold belt with supposed source in the batholith, the writer [16] has pointed out their close association with lamprophyre dikes, which lie along and across them. Some of these dikes have been somewhat altered by the mineralizing fluids and they must therefore have been intruded during the later stages of mineralization. The veins along which they occur show rather shallow-depth characteristics, certainly depths much less than those which existed when the batholith was emplaced. The association of the veins with lamprophyres has been interpreted as evidence of a close relationship between mineralization and igneous activity, with both ores and dikes in fissures produced during the Laramide disturbance and formed as products of early Tertiary igneous activity with roots in a deep magmatic source.

*Coeur d'Alene Region.*—The Coeur d'Alene district is some miles from the Idaho batholith; nevertheless the ore deposits have been correlated with it genetically in the belief that the monzonite intrusion on which the mineralization seems so dependent is an outlier of the batholith, as early expressed by

[14] Anderson, A. L., and Wagner, W. R., A geological reconnaissance in the Little Wood River (Muldoon) district, Blaine County, Idaho: Idaho Bur. Mines and Geology Pamph. 75, pp. 11, 16–17, 1946.

[15] Umpleby, J. B., Westgate, L. G., and Ross, C. P., op. cit., pp. 107–112, 122.

[16] Anderson, A. L., and Wagner, W. R., A geologic reconnaissance of the Hailey gold belt (Camas district), Blaine County, Idaho: Idaho Bur. Mines and Geology Pamph. 76, pp. 6, 13–14, 1946.

Ransome and Calkins,[17] or is continuous with it at depth, as stated by Umpleby and Jones.[18] This today seems to be the generally prevailing view.

Although the writer has not previously expressed himself in print, he, as earlier pointed out by Stewart,[19] can see no petrographic resemblance whatsoever between the monzonite and syenite exposed in the Coeur d'Alene district and the granitic rocks that characterize the Idaho batholith. They obviously belong to entirely different petrogenetic provinces. The rocks most nearly like them are certain small syenite and diorite dikes that cut the batholith in the Atlanta district where they have been interpreted as probable products of early Tertiary igneous activity.[20] The rocks probably most closely related to them in the Coeur d'Alene district are the diabases which occur as dikes throughout the region and which may be early injections of the source magma from which the monzonite and syenite have evolved. The monzonite and syenite apparently had a noritic or dioritic composition before endomorphism converted them to their present state.[21] As elsewhere in the State the ore deposits show a closer timing with intrusion of lamprophyric dikes than with any other rock and again as elsewhere the lamprophyres appear to be just a little later than the ores.

From a structural analysis the writer [22] has concluded that the Osburn fault and associated fractures, which localized and controlled igneous intrusion and mineralization in the Coeur d'Alene district, were caused by shearing around the rigid mass of the Idaho batholith during the Laramide orogeny and further that the fault reached to great depths and facilitated intrusion of early Tertiary magma and genetically related mineralizing fluids. This is in accord with conclusions reached earlier in a study of the mineralization along the western extension of the Osburn fault in Kootenai County [23] where granular and porphyritic intrusives ranging from hornblende diorite to granite and rhyolite porphyry and from diabase to lamprophyre were interpreted as products of early Tertiary igneous activity.

Because of their close association with diabasic and porphyritic dikes along the course of the Hope fault (a fault comparable in every way with the Osburn fault), the ore deposits in the Clark Fork district,[24] which are like those in the Coeur d'Alene district some 35 miles to the southeast, have been assigned a source in early Tertiary magmas. The intrusives along a part of the zone of faulting cut the Nelson batholith (Mesozoic) and exhibit features that indicate rapid cooling at depths much less than those that existed when the batholith was emplaced. Because the Hope fault transgresses Mesozoic structures, it,

[17] Op. cit., U. S. Geol. Survey Prof. Paper 62, pp. 139–140.

[18] Op. cit., U. S. Geol. Survey Bull. 732, p. 149.

[19] Stewart, C. A., A comparison of the Coeur d'Alene monzonite with other plutonic rocks in Idaho: Jour. Geology, vol. 22, pp. 684–688, 1914.

[20] Anderson, A. L., Geology and ore deposits of the Atlanta district, Elmore County, Idaho: Idaho Bur. Mines and Geology Pamph. 49, p. 11, 1939.

[21] Anderson, A. L., Monzonite intrusion and mineralization in the Coeur d'Alene district, Idaho: Econ. Geol., vol. 44, pp. 169–185, 1949.

[22] Anderson, A. L., op. cit., Econ. Geol., vol. 43, pp. 95–98.

[23] Anderson, A. L., Geology and metalliferous deposits of Kootenai County, Idaho: Idaho Bur. Mines and Geology Pamph. 53, pp. 21–25, 1940.

[24] Anderson, A. L., Lead-silver deposits of the Clark Fork district, Bonner County, Idaho: U. S. Geol. Survey Bull. 944-B, pp. 81–83, 1947.

like the Osburn, has been interpreted as a product of the Laramide orogeny and the intrusives directed by it as products of the widespread early Tertiary igneous activity.[25]

*Precious Metal Deposits.*—Deposits previously discussed, except those of the Hailey gold belt, are primarily base-metal deposits of the Wood River and Coeur d'Alene types. The group of precious metal deposits which occur within the batholith have with little hesitation on the part of most writers been rather confidently assigned a source in the Idaho batholith. These deposits are notably different from the base-metal group and from observations in the Wood River area are known to be somewhat older. These deposits include the gold-quartz veins and lodes of Rocky Bar, Boise Basin, and north-central Idaho, the gold-silver veins and lodes of Atlanta, Banner, and Vienna, and the gold-antimony lodes of Yellow Pine.

The gold-quartz veins and lodes in the Rocky Bar district are about typical of the group. They are entirely within the Idaho batholith but they show a much closer association with granophyric and lamprophyric dikes than with the granitic rock of the batholith.[26] The dikes possess features that indicate that they solidified in contact with cold rock and at no great depth below the surface and thus some time after the batholith had cooled and had been brought fairly close to the surface by extensive erosion. The intrusion of the granophyric dikes preceded the mineralization but the lamprophyres came mainly a little later. As the dikes and mineral deposits accord so closely in structural relations and time, their more or less close genetic relationship seems indisputable. Like the intrusives, the ores show shallow characteristics; in fact the deposits are classed as epithermal. It is indeed difficult to reconcile mineralization of such shallow-seated characteristics with deep-seated batholithic activity. Thus the mineralization, like the closely associated dikes, is thought to be a product of early Tertiary igneous activity. That it cannot be mid-Tertiary is evident from the fact that one of the deposits is cut by a porphyry dike similar to one that characterizes the Miocene "porphyry belt" in Boise Basin.

Similar gold-quartz veins and lodes in Boise Basin, which Ross[27] has correlated with the Idaho batholith, yield much the same story as those at Rocky Bar. They also show shallow or epithermal characteristics which are incompatible with an origin in the batholith.[28] They too are commonly accompanied by lamprophyric dikes and locally by somewhat older porphyritic rocks of more silicic composition, which the writer suggests are of early Tertiary age. The source of the ore is thus believed to be a deep-seated magma of early Tertiary age.

In the Elk City and nearby areas of north-central Idaho, Thomson and

[25] Anderson, A. L., op. cit., ECON. GEOL., vol. 43, pp. 96, 98–99.

[26] Anderson, A. L., Geology of the gold-bearing lodes of the Rocky Bar district, Elmore County, Idaho: Idaho Bur. Mines and Geology Pamph. 65, pp. 6–10, 22–23, 1943.

[27] Ross, C. P., Some lode deposits in the northwestern part of the Boise Basin, Idaho: U. S. Geol. Survey Bull. 846-D, p. 272, 1934.

[28] Anderson, A. L., Ore deposits of Boise Basin, Idaho: U. S. Geol. Survey Bull. 944-C, pp. 186–190, 1947.

Ballard [29] as well as Shenon and Reed [30] have correlated the gold-quartz veins with the Idaho batholith, although Shenon and Reed have pointed out that the ore minerals and associated fine-grained quartz were introduced into the veins after an earlier vein quartz had been considerably shattered and that the comb and vuggy nature of much of the quartz, particularly in the Buffalo Hump district, is not characteristic of deposits formed at great depth. They further point out that the veins are near the top of the batholith and that at the time its outer part solidified it must have been covered by a considerable thickness of sedimentary rock. They then infer that the igneous activity possibly extended over a very long period of time and that much of the batholithic cover was eroded before the deposition of the fissure veins or at least before their mineralization. Despite the length of time that must have elapsed between the emplacement of the batholith and mineralization, they still believed the source to be the batholith.

The gold-antimony mineralization in the Yellow Pine district also bears on the problem. Ross [31] has held that the stibnite mineralization took place in Tertiary time (mid-Tertiary epoch) and was superimposed on an earlier gold-quartz mineralization genetically associated with the Idaho batholith. White [32] on the other hand agrees that the antimony is probably Tertiary (mid-Tertiary epoch) but believes the pyrite-arsenopyrite-gold association is also Tertiary (mid-Tertiary epoch) and that it represents the first, high-temperature stage of a process which later, at lower temperatures, caused deposition of antimony. He points out that several lines of evidence indicate that even the early mineralization took place under lower pressure than that which must have existed immediately after the emplacement of the Idaho batholith, which local conditions indicate, at the horizon of the ore zone, took place under a very heavy load. He then states that in contrast the very fine grain of the early sulfides, their association with fine-grained quartz or chalcedony, and the associations of some of the stibnite with albite and arsenopyrite suggest deposition under relatively low pressure, with the temperature high in the early stages but decreasing at a fairly rapid rate. He also believes that the breadth of the shear zone further indicates relatively shallow depth. During a visit to the district in the summer of 1950 the writer noted the resemblance of the early gold mineralization to that at Rocky Bar and Boise Basin and thus believes that both the gold and antimony mineralization belongs to the early Tertiary epoch of metallization.

The gold-silver veins and lodes show the same textural and structural relationships as the gold-quartz veins and lodes. In the Atlanta district [33] the

[29] Thomson, F. A., and Ballard, S. M., Geology and gold resources of north-central Idaho: Idaho Bur. Mines and Geology Bull. 7, p. 50, 1929.

[30] Shenon, P. J., and Reed, J. C., Geology and ore deposits of the Elk City, Orogrande, Buffalo Hump, and Ten Mile districts, Idaho County, Idaho: U. S. Geol. Survey Circ. 9, pp. 29–30, 1934.

[31] Schrader, F. C., and Ross, C. P., Antimony and quicksilver deposits in the Yellow Pine district, Idaho: U. S. Geol. Survey Bull. 780-D, p. 157, 1926.

[32] White, D. E., Antimony deposits of a part of the Yellow Pine district, Valley County, Idaho: U. S. Geol. Survey Bull. 922-I, p. 265, 1940.

[33] Anderson, A. L., op. cit., Idaho Bur. Mines and Geology Pamph. 49, p. 44.

deposits are classed as epithermal and described as occurring in a deeply eroded part of the Idaho batholith but with every indication of having formed at comparatively shallow depth. The igneous rocks most closely associated with the deposits are some dikes of diorite, syenite, and lamprophyre, with many of the lamprophyric dikes extending across the mineralized zone. The igneous activity and mineralization have been assigned to the early Tertiary.

The gold-silver-quartz veins in the Banner district [34] have a higher silver ratio but the mineralization otherwise is much like that at Atlanta. Porphyritic dikes in the district are probably of early Tertiary age rather than mid-Tertiary as originally supposed and the mineralization likewise early Tertiary. In the Vienna district Ross [35] suggests that the lamprophyre that cuts the Vienna lode implies a close relation in time between the mineralization and the intrusion of the batholith, but again the situation is much like that at Atlanta and other districts where the writer has regarded the mineralization as early Tertiary.

*Copper-Cobalt Deposits.*—The relations of some of the copper and locally of some of the copper-cobalt deposits to the Idaho batholith are not too clearly defined. Ross [36] has assigned the copper deposits which occur as replacements along shear zones in quartzitic rocks near Salmon to a source in the Idaho batholith. He postulates that the shear zones are the results of movements related to the intrusion of the batholith and that the alteration and mineralization are the products of waters emanating from the granitic magma. The copper-enriched cobalt deposits in the Blackbird district, which, except for earlier and contemporaneous cobaltite, have all the characteristics of the copper deposits near Salmon, were first regarded as possibly related to the batholith,[37] but on reconsideration of their close association with bodies of gabbro, silicic porphyry, and lamprophyre, the writer decided that the intrusives and the ore deposits are more likely early Tertiary and therefore not associates of the batholith.[38]

*Tungsten Deposits.*—As the tungsten deposits in the Blue Wing district in Lemhi County show such a close association with granite, it might seem at first sight that here is metallization with an indisputable source in the batholith or one of its satellites. The mineralization is certainly intimately associated with the granite, but the writer [39] has shown that the granite is a product of "granitization" (a replaced quartzite) and consequently a product of hydrothermal rather than magmatic processes and that the "granitization" may represent an early intense type of wall-rock alteration with the sulfide and tungsten mineralization occurring as later and cooler phases of the same process. Be-

[34] Anderson, A. L., and Rasor, A. C., Silver mineralization in the Banner district, Boise County, Idaho: Econ. Geol., vol. 29, pp. 371–387, 1934.

[35] Ross, C. P., The Vienna district, Blaine County, Idaho: Idaho Bur. Mines and Geology Pamph. 21, pp. 7, 13, 1927.

[36] Ross, C. P., The copper deposits near Salmon, Idaho: U. S. Geol. Survey Bull. 774, pp. 26–28, 1925.

[37] Anderson, A. L., A preliminary report on the cobalt deposits of the Blackbird district, Lemhi County, Idaho: Idaho Bur. Mines and Geology Pamph. 61, 34 pp., 1943.

[38] Anderson, A. L., Cobalt mineralization in the Blackbird district, Lemhi County, Idaho: Econ. Geol., vol. 42, pp. 24–25, 1947.

[39] Anderson, A. L., Tungsten mineralization at the Ima mine, Blue Wing district, Lemhi County, Idaho: Econ. Geol., vol. 43, pp. 181–206, 1948.

cause the mineralization has so many features in common with Tertiary tungsten mineralization in Colorado and other states of the eastern arc,[40] the writer has concluded that the mineralization must have taken place at the close of the Laramide orogeny and that the deposits therefore are of early Tertiary age.

*Molybdenum Deposits.*—Because of the common association of molybdenite with pegmatitic rocks, one might also expect to find the molybdenite deposits genetically related to the batholith. Such deposits in the Rocky Bar district are reported to be closely associated with intrusive dikes of pegmatite, aplite, diorite, and lamprophyre, all of which are reported as derived from the batholithic magma and formed after the consolidation of the magma.[41] From the published description it appears that the molybdenite mineralization is very similar to that which accompanies the tungsten mineralization in the Blue Wing district in Lemhi County. The molybdenite occurs chiefly in and along quartz veins and in the bordering granitic rock, particularly in the pegmatitic phases of the rock, and is accompanied by considerable pyrite and dark mica, some specularite, a little chalcopyrite, and sphalerite, and locally fluorite and calcite. The mineralization appears to have been accomplished under conditions similar to those in the Blue Wing district, except that the host is the batholith and not quartzite. The molybdenite probably had its source outside the batholith and, because of the close association with diorite and lamprophyre, probably in a deeper magma of early Tertiary age.

Molybdenite deposits are reported elsewhere in Idaho [42] but the available information does not permit adequate evaluation of their genetic associations. In general, they appear to have more or less well-defined "pegmatitic" associations, but they may not be much different in genesis and age from the deposits in the Rocky Bar and Blue Wing districts.

*Summation.*—Not only do the deposits supposedly related to the Idaho batholith show depth characteristics quite incompatible with an origin in the batholith but they also show a very close association with structures produced during the Laramide orogeny and particularly with hypabyssal intrusives of early Tertiary age that utilize these structures. The deposits therefore must belong to the early Tertiary metallogenic epoch rather than to any epoch associated with the activities of the Idaho batholith.

### MID-TERTIARY EPOCH.

The mid-Tertiary, which is the second of the two periods of mineralization recognized by Ross,[43] is well substantiated. This period of mineralization followed the extrusion of the Challis volcanics (Oligocene) and is thus sharply separated from that of early Tertiary age which antedated the volcanics. The ores, however, are more closely associated with granitic and

[40] Kerr, P. F., Tungsten mineralization in the United States: Geol. Soc. America Mem. 15, pp. 5–9, 1946.

[41] Schrader, F. C., Molybdenite in the Rocky Bar district, Idaho: U. S. Geol. Survey Bull. 750-F, pp. 91–92, 1924.

[42] Livingston, D. C., Tungsten, cinnabar, manganese, molybdenum, and tin deposits of Idaho: Univ. of Idaho School of Mines Bull. 2, vol. 14, pp. 40–43, 1919.

[43] Ross, C. P., op. cit., ECON. GEOL., vol. 26, pp. 169–185; op. cit., *in* Ore Deposits of the Western States (Lindgren Volume), pp. 265–272.

porphyritic intrusives that cut the volcanic and older rock than with the volcanic rocks themselves. It appears that the volcanism that occurred on a grand scale in Oligocene time continued into the early Miocene and culminated in diastrophic movements with attendant igneous intrusion and mineralization. The intrusive activity and mineralization apparently came to an end in lower Miocene time, for in the Pearl-Horseshoe Bend [44] and Boise Basin [45] areas the intrusives and related lodes are overspread by beds of the Payette formation and flows of Columbia River basalt (middle or upper Miocene).

The intrusives to which the mineralization shows close association consist of granitic and related porphyries of diverse composition localized along zones of structural weakness either in or along the cores of broad, much faulted anticlinal arches or along broad zones of shearing in the Idaho batholith, forming the so-called "porphyry belts." The intrusive activity apparently attained its maximum development in the Casto quadrangle [46] where the volume of magma appears to have been larger and its diversity greater than at any other place. The intrusives there include bodies of such granitic rock as pink granite, hornblende granite and quartz monzonite, quartz-hornblende-diorite, and various porphyries related to the pink granite such as white granite porphyry, quartz-hornblende-biotite monzonite porphyry, dacite porphyry, andesite porphyry, pink granophyre, coarse granophyre, and lamprophyre. Elsewhere the assemblage of mid-Tertiary intrusives is not so varied and in the Lava Creek district [47] is represented by pink granite, quartz monzonite porphyry, granite porphyry, granite pegmatite, and syenite. The varieties are, however, somewhat more numerous in the Edwardsburg area [48] where the rocks include pink granite and granophyre, granodiorite, quartz diorite, dacite, andesite, and quartz latite porphyry, diorite, and several types of lamprophyre. Diverse rock types are also rather plentiful in the porphyry belts of Pearl-Horseshoe Bend and Boise Basin areas, with dacite porphyry, granite porphyry, syenite porphyry, rhyolite porphyry, certain moderately basic dikes apparently intermediate between rhyolite porphyry and lamprophyre, and several varieties of lamprophyre present in the Pearl-Horseshoe Bend belt,[49] and dacite porphyry, quartz-hornblende-biotite monzonite porphyry, granophyre, rhyolite porphyry, granodiorite porphyry (product of filter pressing) and rhyolite, and lamprophyre represented along the Boise Basin belt.[50] In each of the localities the listing of intrusives is in the approximate order of age from oldest to youngest.

The mineralization like that which occurred earlier in the Tertiary came during the closing stages of igneous activity and was completed just before the

[44] Anderson, A. L., Geology of the Pearl-Horseshoe Bend gold belt, Idaho: Idaho Bur. Mines and Geology Pamph. 41, pp. 12–15, 21, 1934.

[45] Anderson, A. L., op. cit., U. S. Geol. Survey Bull. 944-C, p. 154.

[46] Ross, C. P., Geology and ore deposits of the Casto quadrangle, Idaho: U. S. Geol. Survey Bull. 854, pp. 56–65, 1935.

[47] Anderson, A. L., Geology and ore deposits of the Lava Creek district, Idaho: Idaho Bur. Mines and Geology Pamph. 32, pp. 21–25, 1929; Epithermal mineralization at the Last Chance and Hornsilver mines, Butte County, Idaho: Geol. Soc. America Bull., vol. 58, pp. 455–456, 1947.

[48] Shenon, P. J., and Ross, C. P., Geology and ore deposits near Edwardsburg and Thunder Mountain, Idaho: Idaho Bur. Mines and Geology Pamph. 44, pp. 11–15, 1936.

[49] Anderson, A. L., op. cit., Idaho Bur. Mines and Geology Pamph. 41, pp. 7–12.

[50] Anderson, A. L., op. cit., U. S. Geol. Survey Bull. 944-C, pp. 139–150.

introduction of the lamprophyric dikes. Such dikes are particularly abundant in the mineralized zones at Pearl-Horseshoe Bend, Boise Basin, and Edwardsburg where they commonly lie in and across the lodes. The relationships at Boise Basin are particularly significant, for the successive injections along the Quartsburg-Grimes Pass "porphyry belt" mark the trend or course of differentiation in the deeper parent magma. Mineralization followed closely upon the intrusion of the rhyolite porphyry and rhyolite and was in turn followed by the lamprophyric dikes. Curiously, some of the lamprophyres in the Edwardsburg area occur with and cut diorite and other grade into diorite,[51] whereas in the Pearl-Horseshoe Bend area dikes intermediate between rhyolite porphyry and lamprophyre have phenocrystic characteristics of the rhyolite porphyries and groundmasses of the lamprophyres.[52]

### LATE TERTIARY EPOCH.

The late Tertiary (late Miocene or early Pliocene) mineralization has not generally been distinguished from that of lower Miocene age and may include many of the precious metal deposits now grouped with those of the mid-Tertiary epoch. The recognition of this epoch of metallization is dependent on the age of the basalt and rhyolite cut by the veins in the Silver City district in the southwestern part of the State. Ross [53] has regarded the basalt and rhyolite as the equivalent of the Challis volcanics of south-central Idaho and the ore deposits therefore as of mid-Tertiary age. Kirkham [54] on the other hand considered the basalt a part of the Columbia River lavas (middle or upper Miocene) and the rhyolite as flows which poured over the eroded surface of the basalt and Payette formation in late Miocene or Pliocene time. The relations of similar basalt and rhyolite in the Pearl-Horseshoe Bend area tend to support Kirkham, for the rocks there rest on the eroded surface of the dikes and lodes of lower Miocene age.[55] Thus it seems likely that the mineralization at Silver City (silver-gold-selenium association),[56] which in no way resembles that at Pearl-Horseshoe Bend (gold-base metal), Boise Basin (gold-bismuth base metal), and Lava Creek (chiefly bismuth-base metal), should be assigned to a younger, probably late Miocene or early Pliocene epoch of metallization. Also the deposits elsewhere similar to those at Silver City in possessing a selenium association as those at Custer [57] and other parts of the Salmon River Mountains of central Idaho [58] should be removed from the lower Miocene and reassigned to the later epoch of metallization at the close of the Miocene.

[51] Shenon, P. J., and Ross, C. P., op. cit., Idaho Bur. Mines and Geology Pamph. 44, pp. 15–16.

[52] Anderson, A. L., op. cit., Idaho Bur. Mines and Geology Pamph. 41, pp. 10–11.

[53] Ross, C. P., op. cit., *in* Ore Deposits of the Western States (Lindgren Volume), p. 271.

[54] Kirkham, V. R. D., Igneous geology of southwestern Idaho: Jour. Geology, vol. 39, pp. 579–587, 1931.

[55] Anderson, A. L., op. cit., Idaho Bur. Mines and Geology Pamph. 41, pp. 13–14.

[56] Piper, A. M., and Laney, F. B., Geology and metalliferous resources of the region about Silver City, Idaho: Idaho Bur. Mines and Geology Bull. II, pp. 20–37, 1926.

[57] Anderson, A. L., Silver-gold deposits of the Yankee Fork district, Custer County, Idaho: Idaho Bur. Mines and Geology Pamph. 83, pp. 14, 16–18, 1948.

[58] Ross, C. P., Ore deposits in Tertiary lava in the Salmon River Mountains, Idaho: Idaho Bur. Mines and Geology Pamph. 25, 1927.

These younger deposits do not seem to be intimately associated with intrusive rocks as are those of lower Miocene age and have not been found in association with lamprophyres. The rhyolite appears to be the rock most closely related to them in age.

### QUATERNARY EPOCH.

The most recent mineralization is reflected in certain cinnabar [59] and gold deposits in southwestern Idaho which are contained in beds of the Payette formation (Miocene). The cinnabar occurs along an anticlinal crest and apparently was introduced after the beds had been folded and faulted and after an erosion surface had been carved across the folds. As the folding and erosion surface also involve beds of the Idaho formation (Pliocene and Pleistocene),[60] the mineralization can be no older than early Pleistocene and can be no younger than the early stages of the present cycle of Valley cutting.[61]

The gold deposit in the Payette formation has not been described. It occurs some five or six miles north of Weiser and consists of a broad breccia zone in the Payette formation cemented and in part replaced by chalcedony. The gold content is apparently less than $5 a ton. The chalcedonic mineralization is much like that in the cinnabar deposits and the two are probably genetically related. No intrusive igneous rocks seem to be associated with either.

The extent of this mineralization is not yet known. It is possible that the cinnabar deposits in the Yellow Pine district, which have been described as formed at no great depth and through the agency of hot solutions, possibly hot springs, belong here. The deposits, however, have been related to the general igneous activity of which the intrusion of rhoylite porphyry and the extravasation of the Tertiary volcanic rocks (Challis volcanics) are regarded as manifestations.[62] The sulfur deposits near Soda Springs, though not metalliferous, probably belong to this epoch. The deposits are near volcanic centers and the springs today are giving off hydrogen sulfide and carbon dioxide and are depositing sulfur.[63]

### SUMMARY AND CONCLUSIONS.

No less than five metallogenic epochs are represented within the State of Idaho. These are the (1) late Precambrian, (2) early Tertiary, (3) mid-Tertiary, (4) late Tertiary, and (5) Quaternary. Each epoch is rather sharply delineated stratigraphically—the Precambrian, by confinement of the deposits to the Purcell sills and by close association with volcanic rocks of late Precambrian age; the early Tertiary, by restriction of its deposits to rocks as

[59] Anderson, A. L., Geology of the Alameden quicksilver mine near Weiser, Idaho: Idaho Bur. Mines and Geology Pamph. 55, 9 pp., 1941.

[60] Kirkham, V. R. D., Revision of the Payette and Idaho formation: Jour. Geology, vol. 38, pp. 652–663, 1930.

[61] Anderson, A. L., op. cit., Idaho Bur. Mines and Geology Pamph. 55, pp. 8–9.

[62] Larsen, E. S., and Livingston, D. C., Geology of the Yellow Pine cinnabar-mining district, Idaho: U. S. Geol. Survey Bull. 715-F, pp. 79–80, 1920.

[63] Richards, R. W., and Bridges, J. H., Sulfur deposits near Soda Springs, Idaho: U. S. Geol. Survey Bull. 470-J, pp. 499–503, 1910.

young as the Idaho batholith (late Mesozoic) but not as young as the Challis volcanics (Oligocene); the mid-Tertiary, to rocks as young as the Challis volcanics but not as young as the Columbia River basalt and Payette formation (middle or upper Miocene); the late Tertiary, to rocks as young as the rhyolite (late Miocene or early Pliocene) that rests unconformably on the Columbia River basalt and Payette formation but apparently not as young as the Idaho formation (Pliocene and Pleistocene); and the Quaternary, to strata deformed in late Pliocene or early Pleistocene time but before the present cycle of valley cutting.

The role of the Idaho batholith as a producer of ore deposits must be discredited. Most of the deposits supposedly related to it have features of deposits formed at comparatively shallow depths—at pressures and depths much less than existed when the batholith was emplaced—and at temperatures much lower than might be expected in deposits formed in or near its margin or its satellites. The development of the batholith itself was not such as to lend much encouragment to the formation of anything except aplites and pegmatites. It was not emplaced as a unit, as has been generally supposed, but its structural relations indicate a three-fold emplacement, the earliest during the late but still rather intense stage of the Nevadan orogeny, the second during the later, less intense stage of that orogeny, and the third during the Laramide. Thus the emplacement of the batholith took place sporadically over a long interval of time ranging from the close of the Jurassic to the close of the Cretaceous, and the only products definitely related to it are the aplites and pegmatites formed during the closing stages of each of the emplacements. The ore deposits which have been regarded as associates have structural and textural characteristics incompatible with a source in the batholith and show a much more direct relationship to hypabyssal intrusives that cut the batholith or to structural features formed subsequent to the emplacement of the batholith. Apparently the batholith by its very mode of formation was incapable of producing metalliferous ores. Instead the source of the ores appears to have been in a magma that gave rise to the early Tertiary intrusives, and that magma apparently had its origin in the basic crust beneath the batholith.

The relationships of the metallization to the igneous activity in each of the epochs tend to point rather definitely to a magma as the source of the ores and originally to one of rather basic composition. In the Precambrian the ore in one case occurs as a segregation within a basic (originally gabbroic) sill and in another in close association with flows of basic (basaltic) composition. In the early Tertiary epoch the earliest rock intruded was either a diabase or diorite; then in many places followed a succession of progressively less basic intrusives, either porphyritic or non-porphyritic, which show the trend of differentiation in the deep magma source. The series generally ended in a rhyolitic porphyry or other alkalic rock and was then followed by the metallizing fluids, closely accompanied by the intrusion of lamprophyre.

The mid-Tertiary repeats most of the features of the early Tertiary, although the earliest injected rock was slightly less basic—a dacite porphyry

or diorite rather than a diabase or gabbro. The succession of intrusives that followed marks the progressive changes taking place in the consolidating magma below, from basic to silicic, with rhyolite porphyry or rhyolite representing the last of the magma to be expelled before the metallization and introduction of lamprophyres, the final product after metallization.

In the late Tertiary epoch the metallization was preceded by flows of basalt and then after an interval of erosion by extrusion of the rhyolite. The metallization apparently was not accompanied by dike intrusion, not even by lamprophyres, but the lava sequence suggests a change in composition of the magma body below from basic to silicic before metallization.

In the Quaternary epoch closely associated igneous rocks either intrusive or extrusive appear lacking, except in the case of the sulfur deposits where proximity to volcanic centers suggests a volcanic origin for the hydrogen sulfide and carbon dioxide. The cinnabar and gold deposits possess features of hydrothermal (hot spring) origin and probably received their metals from some deep magmatic source.

Thus it appears that the ores in at least four of the epochs originated in basic magmas or magmas that originally were basic and were tapped from deep sources, perhaps at different levels of the basic crust beneath the granite overlay. The metals of the fifth epoch, the one apparently without closely accompanying igneous rocks, probably also had their source deep within the earth.

The close timing of the metallization with the last stages of igneous activity invites further speculation as to the part played by the lamprophyres. Where the porphyry sequence is well developed, the metallization appears to follow shortly after the intrusion of the rhyolite porphyries, the most alkalic and silicic of the magmatic differentiates. The remaining residuum also appears to be more or less abundantly enriched in alkalies, for in many places the mineralizing fluids emitted in advance of the ore provoked extensive sericitization and even granitization of the wall rocks. Then after the ore has been introduced into the altered rock above, the lamprophyres, the last remaining magmatic "juices," were expelled upward along the same channelways. Their introduction marks the end of mineralization and igneous activity.

However, the problem of the lamprophyre has not been solved. These dark rocks combine features of both the basic and alkalic rocks. In their phenocrysts they appear to be allied with the basic rocks, particularly to the peridotites or gabbros (many of the early Tertiary lamprophyres in Idaho are olivine bearing), but their groundmasses suggest alliance with the alkalic rocks. That the lamprophyre is a product of the magma seems certain, for, as mentioned earlier, some of the lamprophyres in the Pearl-Horseshoe Bend area show transition into rhyolite porphyry and some at Edwardsburg into diorite. Could it be that the alkalic-rich residuum formed during differentiation and concentrated with the ores in the deep or bottom part of the magma chamber came in contact with early basic segregations or the basic floors and walls of the chamber, dissolved some of the rock to enrich itself in basic con-

stituents, and then was squeezed out as "lamprophyric magma" on the heels of the metallizing fluids?

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# GEOCHEMICAL TECHNIQUES AS APPLIED IN RECENT INVESTIGATIONS IN THE TINTIC DISTRICT, UTAH.[1]

HY ALMOND AND H. T. MORRIS.

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ABSTRACT.

Field techniques for the rapid extraction and estimation of copper, lead, and zinc from altered rock are described, together with their application in the Tintic district, Utah. Either sulfuric acid or an acetic acid-ammonium acetate reagent is feasible as an extractant; but of these two, sulfuric acid is preferred.

Data obtained by partial extraction methods show that zinc and lead are concentrated in altered extrusive rocks 350 to 500 feet above a horizontal, pipelike ore body in limestone, where the extrusive rocks are cut by a fracture zone related to a strong premineral cross fault. Such concentrations are absent in altered but unbrecciated igneous rocks above the continuation of the same ore body in an unfaulted area.


[1] Published by permission of the Director, U. S. Geological Survey.

In many places premineral alteration diminished the original heavy metal content of the igneous rocks, and in unfractured extrusive rocks the hydrothermally leached rock yields a negative anomaly even though the rock lies only a short distance above ore.

## INTRODUCTION.

THE relation of heavy metals in altered rock at the surface to blind ore bodies in the East Tintic district, Utah, was investigated during 1947 by T. S. Lovering, V. P. Sokoloff, and H. T. Morris (10).[2] Their data were obtained by colorimetric wet methods. As a result of their study, "concentrations of heavy metals believed to be chiefly zinc, with some lead and rarely copper (?), were found in pyritized rhyolite above and up rake from known blind ore bodies, and were lacking in similarly altered rhyolite underlain by barren rocks."

From this qualitative study, Lovering, Sokoloff, and Morris concluded that the acetic acid-ammonium acetate solution selected only the fraction of the total heavy-metal content introduced by the ore-forming solutions. This fraction was believed to be small compared with the total amount of heavy metal present in these rocks, and the work suggested that a positive test by the partial extraction method would reveal the location of upward movement of ore solution.

Quantitative geochemical investigations undertaken by the present authors during the field season of 1948 had three objectives: first, to ascertain the amounts of extractable copper, zinc, and lead present in altered igneous rocks adjacent to ore; second, to determine, if possible, the spatial relationships of heavy metal concentrations to unexposed ore bodies; and third, to improve the chemical methods. The chemical procedures developed, and the results obtained by them, are described in this report along with the geological and geochemical interpretations of the positive and negative geochemical anomalies established during the 1948 investigation.

This study was suggested by T. S. Lovering of the U. S. Geological Survey. The authors are indebted to him for guidance and stimulating discussion during the course of the investigation and the preparation of the report. Mr. Fred Hansen and Mr. Ernest Boyne of the Tintic Standard Mining Co. generously allowed the use of engineering and geologic maps of the Iron Blossom mines and also gave valuable information concerning the occurrence and grade of ore at that property. C. H. Hill, Jr., assisted in collecting and preparing some of the samples.

The listing of authors on this paper is alphabetical; each assumes equal responsibility for all the ideas presented. Almond is to be credited, however, with the analytical work and the adaptation of chemical methods for the field problem, and Morris is to be credited with the geological interpretations.

## CHEMICAL PROCEDURE.

Two extractants were used—a sulfuric acid reagent and an acetic acid-ammonium acetate reagent. Of these, the sulfuric acid reagent was preferred for reasons discussed later. Although neither of these reagents extracted the

[2] Numbers in parentheses refer to Bibliography at end of paper.

total copper, lead, and zinc from the rock samples, the method of partial extraction described here was adopted because it was simple and fast.

Extractions by the methods used depend on the state of subdivision of the sample, the chemical form of the element sought, and the time and temperature of treatment. In spite of these many variables, the partial extraction procedures gave results as significant in finding enriched zones as results obtained by expensive and laborious laboratory methods for total copper, lead, and zinc (Table 1).

The methods for determining traces of copper, zinc, and lead described here are standard colorimetric procedures varied to serve the field need for fast analyses. The organic reagent dithizone (diphenylthiocarbazone) described by various writers is used to make estimations of heavy metals on aliquots of the sulfuric acid- or the acetic acid-ammonium acetate extract. The monograph by E. B. Sandell (18) contains instructions on use of the reagent.

Dithizone is a solid, readily soluble in carbon tetrachloride or chloroform. Dilute solutions of dithizone in carbon tetrachloride are green. A carbon tetrachloride solution of dithizone shaken with an aqueous solution of certain heavy metals forms a colored dithizonate that is generally soluble in the organic solvent. The color of the dithizonate varies with the metal present. Dithizone dissolved in basic solution forms the alkali metal dithizonate (18). In the presence of complexing agents at controlled pH, specific heavy metals may be estimated directly with dithizone provided other reacting metals are not present greatly in excess of their usual occurrence. At a pH of 3, under the extraction conditions of these tests, only copper reacts with dithizone. At a pH of 4.5 to 5.5, zinc in these test solutions reacts with dithizone, and in the presence of sodium thiosulfate the reaction of elements other than zinc is largely prevented (7). Lead may be estimated best with dithizone at pH of 8.5 in the presence of potassium cyanide, which forms complexes with other reacting metals present.

Copper and zinc are estimated by the "mixed" color method. In this method both unreacted dithizone and the colored metal dithizonate remain in the carbon tetrachloride phase. The hue of the solution is compared with that of a series of standards similarly prepared.

Lead is determined by the monocolor method, wherein the excess of dithizone is extracted with a dilute alkaline solution, and the intensity of pink remaining in the carbon tetrachloride phase is a measure of the amount of the lead present. The color is compared visually with standard pink lead dithizonate solutions similarly prepared.

Dithizone solutions should be stored in pyrex and the stock solutions kept cool. All glassware should be pyrex, washed with aqua regia and rinsed several times with demineralized water. Mortars, sieves, and spatulas must be essentially free of heavy metals.

To avoid confusion certain terms are defined. The definitions given below are followed throughout this paper.

1. Aliquot. A measured portion.
2. γ A symbol meaning microgram.
3. Microgram. One millionth of a gram.

4. ppm. Parts per million. One microgram of a certain element in a one gram sample equals one part per million (1 ppm).
5. Reflux. Boiling maintained for an extended period of time without appreciable loss of volume.
6. Heavy metal. A misnomer. As used here heavy metals are those which react with dithizone.
7. Anomaly. A positive or negative geochemical anomaly is an area where the metal content of the rock is respectively greater or less than that of normal, unaltered rock.

*Preferred Method. Sulfuric Acid Extraction and Estimation.*

*Reagents.*—Potassium cyanide, 10 percent. Prepare an approximately saturated solution (50 g in 100 ml of solution). To remove traces of lead, shake with successive small portions of a chloroform solution of dithizone until the dithizone solution remains green. Wash the excess dithizone from the aqueous layer with pure chloroform, and dilute the cyanide solution to 10 percent. (Caution: This reagent is toxic and pipettes should never be used. The gas evolved when acid reacts with potassium cyanide is lethal, and no antidotes are known.)

Sodium thiosulfate, 50 g of $Na_2S_2O_3 \cdot 5H_2O$ in 100 ml of water. Shake with 0.01 percent carbon tetrachloride solution of dithizone (see below). Remove excess dithizone by successive shakings with pure carbon tetrachloride.

Sulfuric acid, 1 N. Dilute 28.5 ml of concentrated sulfuric acid to 1 liter.

Ammonium hydroxide, 1 N. Dilute 70 ml concentrated ammonia to 1 liter.

Hydrochloric acid, 1 N. Dilute 180.2 g of constant boiling acid to 1 liter.

Ammonium citrate, 10 percent. Remove reacting metals by extracting with successive portions of 0.01 percent solution of dithizone (see below) until carbon tetrachloride phase is green. Remove excess dithizone by shaking with carbon tetrachloride.

Acetate buffer, pH about 4.75. Mix equal volumes of 2 N sodium acetate and 2 N acetic acid and remove reacting heavy metals by shaking with 0.01 percent dithizone solution.

Dithizone (diphenylthiocarbazone), 0.01 percent (weight/volume) in carbon tetrachloride.

Dithizone, 0.001 percent. Dilute 0.01 percent dithizone tenfold with $CCl_4$. Prepare daily and keep in a dark pyrex bottle.

Thymol blue, 0.04 percent. Dissolve 0.1 g of the solid in 4.3 ml of 0.05 N NaOH and dilute to 250 ml.

*Equipment.*—Iron test tube rack. The following design is intended to minimize bumping during refluxing. Two iron disks 8 inches in diameter are held about 5 inches apart, one above the other, by an iron rod through the centers of the disks. The holes in the upper disk are large enough to let the test tubes pass through; and the holes in the lower disk are only large enough to hold the test tubes in a fixed position without letting them pass through.

Resin demineralizer. Pass stream water or tap water through the demineralizer at a rate up to 8 gallons per hour. Purity of the effluent water should

be checked frequently with dithizone. The writers used the Barnstead Bantam Demineralizer.

Iron mortar and pestle, essentially free of heavy metals, of convenient size to crush 10-g samples.

Balance. Sensitivity to 0.01 g is satisfactory.

Hot plate (preferable) or gasoline burner.

Sieve. 80-mesh silk or other noncontaminating screen.

Pyrex glassware:

Pipettes—series from 0.1 ml to 10 ml.

27 test tubes 25 by 200 mm marked at 30 and 40 ml.

6 cylinders 100 ml; graduated and glass stoppered.

3 funnels, separatory; 125 ml, glass stoppered.

*Preparation of Sample.*—Chip fractions of the rock samples and grind in a mortar to pass through an 80-mesh sieve. Quarter the finely ground material in the usual manner.

*Extraction.*—Place one gram of the quartered sample in a 25 by 200 mm pyrex test tube. Prepare eight samples at the same time. Add 30 ml of 1 N sulfuric acid and reflux for 30 minutes. Dilute to 40 ml; reflux for an additional 5 minutes and allow to cool. Take aliquots directly from the supernatant liquid.

*Estimation of Copper.*—Transfer a 2-ml aliquot of the sulfuric acid solution to a 100-ml glass-stoppered pyrex graduated cylinder. Add 2 to 3 drops of thymol blue indicator, 1 ml of the 10 percent ammonium citrate solution, and then 1 N ammonium hydroxide until the solution begins to turn yellow (pH 2.5 to 3). If too much ammonium hydroxide has been added and no pink color remains, back titrate with 1 N HCl until the pink reappears. Add 5 ml of 0.001 percent fresh solution of dithizone and shake for 2 minutes. Compare the mixed color produced with standard copper solutions. Four micrograms of copper gives a gray color in the carbon tetrachloride; 5 micrograms, a blue; and 6 micrograms, a purple. Less than 4 micrograms of copper gives no definite color change, whereas more than 6 micrograms gives a pink color. If the first aliquot does not give a color in the suitable range, repeat, using an appropriate aliquot.

*Estimation of Zinc.*—Transfer a 1-ml aliquot from the sulfuric acid extract to a 100-ml glass-stoppered pyrex graduated cylinder. Add 0.5 ml of the 10 percent ammonium citrate, 2 to 3 drops of thymol blue, and 1 N ammonium hydroxide until the color of the solution is yellow (pH 2.8). Dilute to about 10 ml, add 1 ml of the purified sodium acetate solution for a buffer (pH 4.5 to 5.5), and 1 ml of 50 percent sodium thiosulfate solution. Add 5 ml of 0.001 percent fresh solution of dithizone and shake for 1 minute. Estimate the zinc in the carbon tetrachloride phase by the mixed color method. Zinc gives the following colors: ½ microgram, blue-green; 1 microgram, blue; 2 micrograms, purple; 3 micrograms, violet; 4 micrograms or more, purplish red. Use a smaller aliquot in the event a purplish red color results, or a larger aliquot if the green remains apparently unchanged.

*Estimation of Lead.*—Transfer a 2-ml aliquot from the original 40-ml solution to a 125-ml pyrex separatory funnel. Add 5 ml of 10 percent ammonium citrate, 2 drops of thymol blue, and sufficient ammonium hydroxide to turn the solution distinctly yellow. Add 10 percent potassium cyanide until the entire solution just turns blue (pH about 8.5). Add 5 ml of 0.001 percent freshly prepared dithizone solution and shake gently for 5 seconds. Drain the bottom layer containing the lead dithizonate into a 100-ml glass-stoppered pyrex graduated cylinder containing 10 ml of 0.1 percent potassium cyanide solution. Shake the mixture for 3 seconds. Excess dithizone is now in the aqueous phase and the pink lead dithizonate is in the carbon tetrachloride phase. From standards similarly prepared, estimate the amount of lead present. The sensitivity of the test ranges from 1 to 3 micrograms of lead.

### *Alternate Method. Acetic Acid-Ammonium Acetate Extraction and Estimation.*

*Reagents.*—Acetic acid, glacial. Some lots are low in heavy metals and may be used directly from stock solutions.

Ammonium hydroxide, concentrated.

Hydrochloric acid, 1 N. (See preferred method.)

*See preferred method for the following:* Potassium cyanide; sodium thiosulfate; dithizone 0.01 and 0.001 percent; acetate buffer; thymol blue.

*Equipment.*—Mortar—Plattner type.

Balance, test tube holder, hot plate, demineralizer (see preferred method).

Pyrex glassware:

6 funnels, long stemmed, 60 degrees.

6 beakers, 250 ml.

Pipettes, separatory funnels, cylinders (see preferred method).

*Preparation of Sample.*—Crush the rock sample in the Plattner-type diamond mortar to the texture of coarse sand, about 10 mesh. Other crushing equipment may be used, but if an iron mortar or pestle is used, do not effect a grinding motion. Quarter the crushed rock and proceed with the extraction.

*Extraction.*—Weigh a 2-g fraction of the crushed quartered sample and place in a 250-ml pyrex beaker. Add about 25 ml of water and 1 ml of glacial acetic acid. Stir for 1 minute. Add 1.5 ml of concentrated $NH_4OH$ and heat to boiling. Filter, and repeat this extraction. Wash twice with hot water. Combine the filtrates in a 100-ml graduated cylinder, dilute to 100 ml and shake vigorously.

*Estimation of Copper.*—Transfer a 25-ml aliquot to the 100-ml cylinder. Add 2 to 3 drops of thymol blue and add dropwise 1 N hydrochloric acid until the solution begins to turn yellow (pH 2.5 to 3). Add 5 ml of 0.001 percent freshly prepared dithizone and shake the mixture for 2 minutes. Estimate visually by the mixed color method as described under preferred method.

*Estimation of Zinc.*—Transfer a 10-ml aliquot of the ammonium acetate solution of the sample, 2 ml of the acetate buffer (pH 4.5 to 5.5), and 1 ml of 50 percent sodium thiosulfate to the 100-ml cylinder. Add 5 ml of 0.001 percent

dithizone and shake the mixture for 1 minute. Compare with standard solutions by the mixed color method, as described under preferred method.

*Estimation of Lead.*—From the ammonium acetate extraction transfer a 5-ml aliquot into a 125-ml glass-stoppered separatory funnel. Add 2 to 3 drops of thymol blue and sufficient 10 percent potassium cyanide to turn the solution barely blue (pH about 8.5). Add 5 ml of 0.001 percent dithizone and shake gently for 5 seconds. Separate the carbon tetrachloride phase into the 100-ml cylinder containing 10 ml of 0.1 percent potassium cyanide and shake for 3 seconds. Estimate as described under lead estimation by the preferred method.

## *Discussion.*

Certain weaknesses in the acetate extraction method should be noted. The acetate reagent extracts only part of the significant lead and zinc present and none of the copper. In an attempt to effect a more complete extraction, the coarse sample was finely ground in an iron mortar. No lead could be extracted from this sample. R. E. Stevens, of the U. S. Geological Survey, in an oral communication suggested the following explanation for this action:

TABLE 1

COMPARISON OF EXTRACTION TECHNIQUES ON SAMPLES OF QUARTZ MONZONITE ADJACENT TO, AND REMOTE FROM ORE.

| Sample no. | | Zinc (ppm) | | | Lead (ppm) | | |
|---|---|---|---|---|---|---|---|
| | | Acetic acid-ammonium acetate | Sulfuric acid | Total[1] | Acetic acid-ammonium acetate | Sulfuric acid | Total[1] |
| Remote from ore | 1 | 2 | 2 | 32 | 0.8 | 8 | 27 |
| | 2 | 2 | 5 | 47 | 1.5 | 11 | 28 |
| | 3 | 13 | 14 | 68 | 2.5 | 1.5 | 30 |
| | 4 | 4 | 1 | 28 | 0.5 | 7 | 32 |
| Intermediate | 5 | 2 | 5 | 76 | 2 | 3 | 45 |
| | 6 | 3 | 20 | 80 | 1.5 | 10 | 80 |
| Adjacent to ore | 7 | 3 | 6 | 144 | 3 | 5 | 110 |
| | 8 | 8 | 130 | 200 | 7 | 40 | 225 |
| | 9 | 13 | 150 | 340 | 25 | 150 | 225 |
| | 10 | 5 | 20 | 140 | 5 | 60 | 340 |
| | 11 | 9 | 50 | 270 | 90 | 200 | 750 |

[1] Sample decomposed with hydrofluoric acid-perchloric acid and estimated by Holmes' method (5).

Fine grinding chipped some iron from the mortar and the free iron remained dispersed throughout the sample. Upon the addition of acetic acid, the dispersed iron reduced the dissolved lead to metallic lead and thus removed it from solution.

An ideal extractant would be one that extracts specifically the relatively more soluble minerals that are derived from solutions moving away from ore bodies, leaving the more resistant primary minerals unattacked. Comparative

data on the two extraction procedures are given by the analyses of fresh to altered rhyolite adjacent to an exposed vein in the main Tintic district, Utah. The results obtained on these samples by the acetate and sulfuric acid extractions are compared with results obtained by determination of total zinc and lead (Table 1).

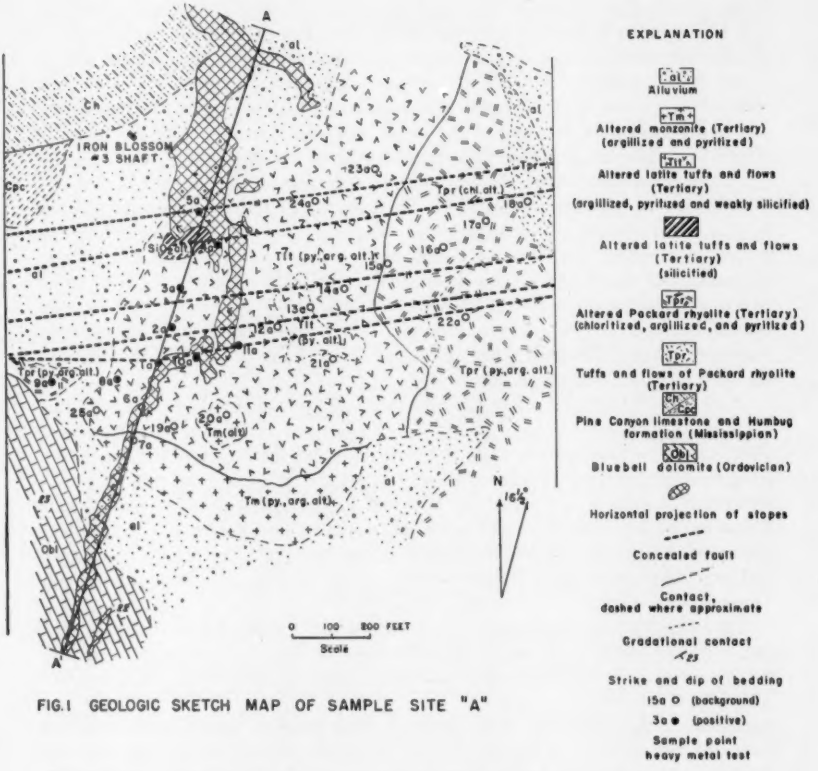


FIG. 1 GEOLOGIC SKETCH MAP OF SAMPLE SITE "A"

Sulfuric acid extractions are useful in determining the small differences in heavy metal content that may exist in two samples, whereas the acetate extraction may be used to locate the presence of relatively large amounts of lead in rock samples. The sulfuric acid extraction is fast, adequately accurate, and applicable to field conditions. The method is easy to learn and is inexpensive in comparison with the various methods for making determinations of total heavy metal by laboratory procedures. A high degree of training is not necessary.

## ANOMALIES RELATED TO MINERALIZATION.

The areas above known ore bodies in the Iron Blossom ore zone of the main Tintic mining district (8) were selected for study because, as shown in Figures 1, 2, 3, and 4, they include both fractured and unfractured pre-mineral cap rocks that overlie narrow, persistent, shallow, horizontal ore bodies. The ore bodies of the Iron Blossom ore zone occur in Paleozoic limestones and dolomites that are overlain in part by altered, pre-ore Tertiary latite flows and tabular intrusive monzonite. A positive geochemical anomaly in these altered rocks would indicate that the ore-depositing solutions rose along the same channelways used by the earlier but genetically related solutions that caused the hydrothermal alteration of the latite and monzonite. Such an anomaly would be a valuable guide in exploration for blind ore deposits.

Altered bedrock above the horizontal projection of stoped ore bodies was sampled on a predetermined grid modified by the distribution of outcrops and by the accumulating geochemical data. Early in the work, care was taken to minimize the sampling error by taking many chips as a composite sample representative of the outcrop. As work progressed, a correlation between easily extractable heavy metals and the degree of brecciation and intensity of alteration of the rock became evident. Samples were then preferentially chosen from fractured, altered material when it was present. Care was taken in collecting samples to avoid contamination.

*Site A.*—An area of altered quartz latite, latite, and monzonite a few hundred feet south of the Iron Blossom No. 3 shaft was selected as the first sampling site. It was designated site A. The main ore shoot is in dolomite underlying the igneous rocks. It has the form of a flattened horizontal pipe 20 to 100 feet thick and 30 to 170 feet wide and lies 300 to 500 feet below the surface. The ore consists chiefly of cerussite, horn silver, and residual argentiferous galena in a jasperoid and barite gangue. Less important ore bodies of enargite and argentite occur in a 700-foot vertical zone beneath this lead-silver shoot (Figs. 1, 2).

At a depth of approximately 500 feet below the sampling site, the ore bodies pass with relatively little disturbance through the Sioux-Ajax fault, a persistent, major pre-ore fault zone that is 350 feet wide at this point. Although this fault is pre-lava as well as pre-ore, it is reflected in the tuff-breccias, flows, and intrusives at the surface by wide zones of chloritization, argillization, pyritization, and silicification. These pervasive alteration halos delineate hydrothermal conduits rather than ore bodies and are the result of solutions distinct from the ore-depositing solutions. Nearly all of the ore bodies in the district, however, are localized in restricted parts of these hydrothermal conduits. Geochemical prospecting for blind ore bodies may be confined to areas of altered rock that broadly outline the controlling structures.

A graphic summary of the field test data at site A, near the Iron Blossom No. 3 shaft, is presented in Figure 1 with the accompanying Table 2. The positive heavy metal anomaly evident in the altered rock is confined to the fault zone and is further restricted to the area directly above ore. Beyond the fissured area (samples Nos. 6a, 7a, 19a, 20a, and 25a) lead, zinc, and copper ap-

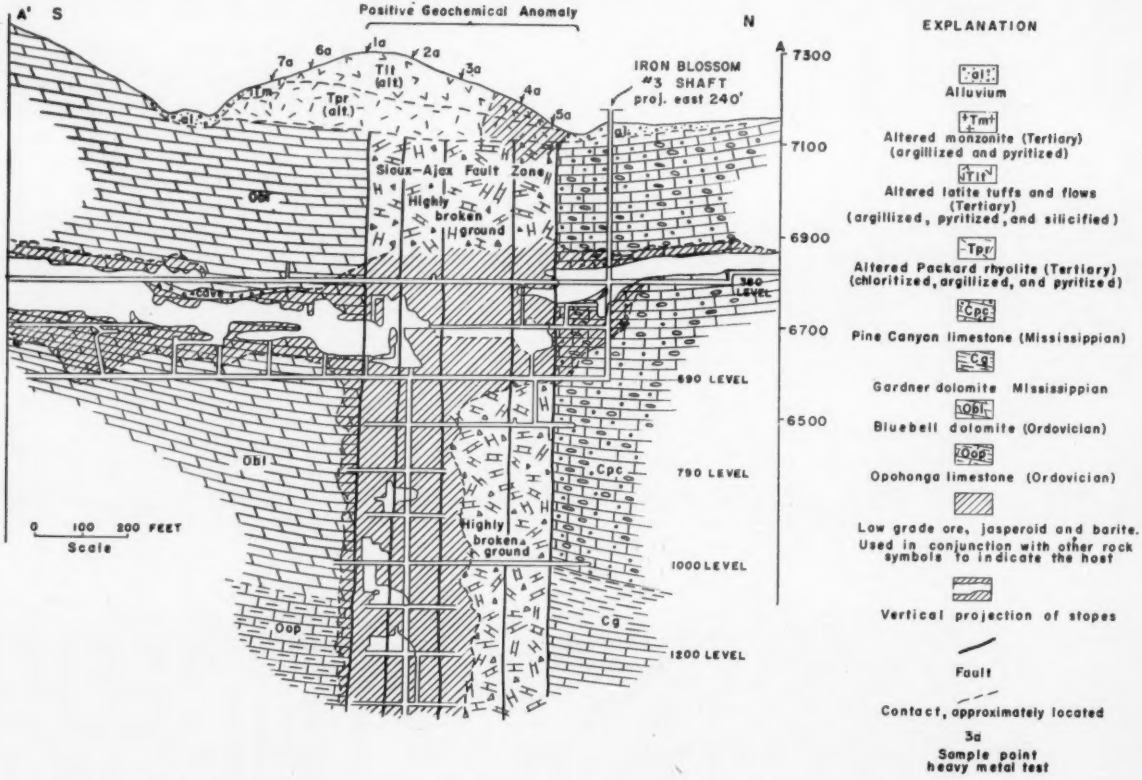


FIG. 2 LONGITUDINAL SECTION THROUGH ORE BODIES AT SAMPLE SITE "A"

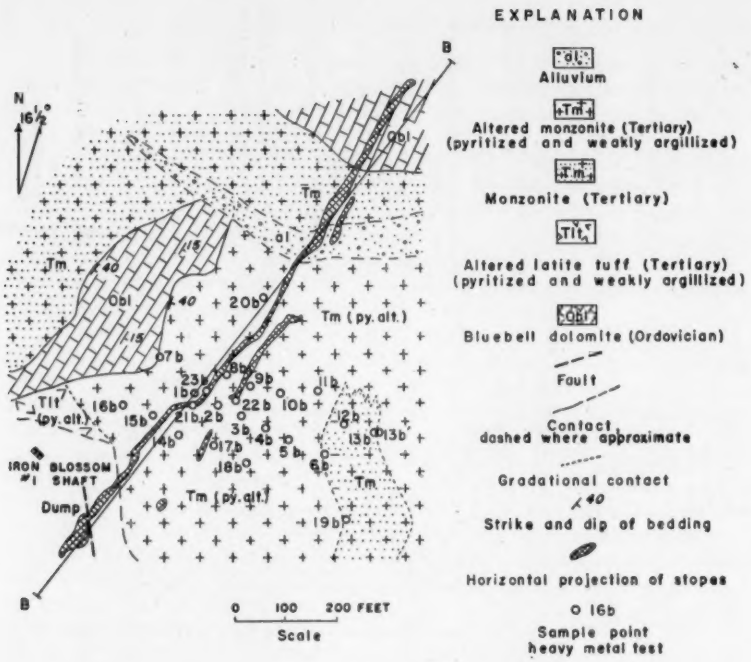


FIG. 3 GEOLOGIC SKETCH MAP OF SAMPLE SITE "B"

parently were not introduced in appreciable quantities. Study of thin sections showed that the heavy metal concentration is apparently related also to a mass of fractured, partly silicified, latite breccia.

This pattern strongly suggests that, if suitable channelways are available, hidden ore bodies are reflected at the surface by concentrations of heavy metals introduced by the near-spent ore-depositing solutions up rake from ore. An unknown area can be prospected for ore cheaply and quickly by this method, and mineralization should be indicated if the geological conditions are similar to those at site A.

*Site B.*—A second sampling area, site B, is near the Iron Blossom No. 1 shaft 1600 feet south of site A. The ore bodies at site B are in thermally metamorphosed dolomite that lies beneath a nearly horizontal, dikelike body of altered monzonite (Figs. 3, 4).

The ore zone is veinlike, ranging from a few feet to 70 or 80 feet in width and from 100 to several hundred feet in height. Its uppermost point at the sample site is 50 feet below the surface. The vein walls are well defined in

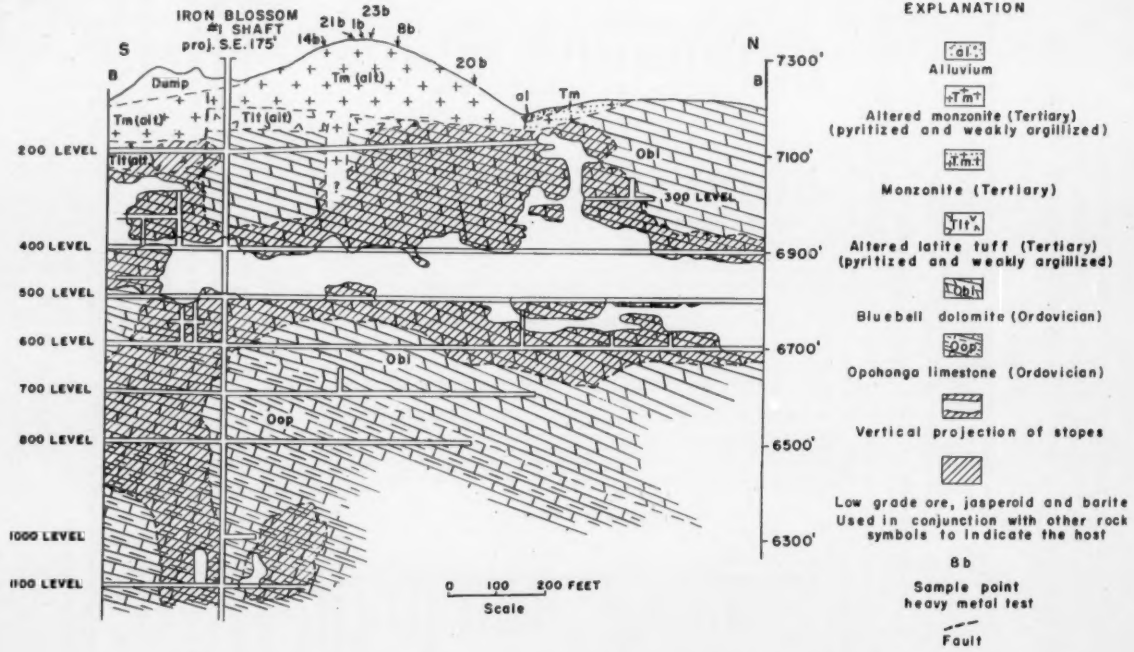


FIG. 4 LONGITUDINAL SECTION THROUGH ORE BODIES AT SAMPLE SITE "B"

many places, but no persistent fracturing is recognizable either in the dolomite or the overlying altered igneous rock. The lead, copper, and silver ore bodies appear to be localized within an obscure pre-monzonite fissure system, however, and show evidence of origin by both replacement and fissure filling.

TABLE 2

RESULTS OF EXTRACTION OF HEAVY METALS FROM ALTERED EXTRUSIVE QUARTZ LATITE AND LATITE ABOVE IRON BLOSSOM NO. 3 ORE BODIES. (SITE A.)

| Sample no.[1] | Acetic acid-ammonium acetate extraction | | Sulfuric acid extraction | | | Alteration intensity |
|---|---|---|---|---|---|---|
| | Zn (ppm) | Pb (ppm) | Cu (ppm) | Zn (ppm) | Pb (ppm) | |
| 1a | 20 | 50 | 12 | 20 | 400 | Intense |
| 2a | 20 | 45 | 13 | 16 | 320 | Intense |
| 3a | 13 | 25 | 16 | 16 | 300 | Intense |
| 4a | 8 | 23 | 10 | 6 | 30 | Intense |
| 5a | 37 | 3 | 14 | 20 | 100 | Intense |
| 6a | 3 | 1 | 3 | 8 | 4 | Intense |
| 7a | 2 | 0 | N.D.[2] | 4 | 0 | Intense |
| 8a | 3 | 2 | 17 | 6 | 60 | Intense |
| 9a | 5 | 0 | 24 | 20 | 60 | Intense |
| 10a | 2 | 2 | 8 | 10 | 20 | Moderate |
| 11a | 3 | 1 | 32 | 15 | 30 | Intense |
| 12a | 5 | 3 | N.D.[2] | 8 | 2 | Moderate |
| 13a | 9 | 5 | 8 | 2 | 1 | Intense |
| 14a | 1 | 1 | 8 | 8 | 5 | Intense |
| 15a | 1 | 1 | 5 | 8 | 1 | Moderate |
| 16a | 3 | 5 | 4 | 8 | 0 | Moderate |
| 17a | 1 | 1 | 4 | 6 | 1 | Moderate |
| 18a | 1 | 1 | 5 | 18 | 4 | Low |
| 19a | 1 | 0 | 6 | 8 | 1 | Intense |
| 20a | 1 | 0 | 10 | 5 | 1 | Intense[3] |
| 21a | 1 | 0 | 11 | 9 | 2 | Moderate |
| 22a | 1 | 0 | 4 | 6 | 1 | Moderate |
| 23a | 2 | 0 | 9 | 10 | 2 | Intense |
| 24a | 1 | 0 | 9 | 5 | 0 | Intense |
| 25a | 1 | 0 | 4 | 9 | 1 | Intense |

[1] For location see Figure 1.
[2] Not determined.
[3] Monzonite.

The monzonite overlying the ore zone is structurally and chemically similar to the cappings of extrusive lava at site A. It is affected by weak argillic and comparatively intense pyritic alteration close to the ore and by a pervasive chloritic-epidotic-calcitic alteration at a greater distance. In general the alteration at site B is weaker than that associated with ore at site A.

The field analyses (Table 3) show no positive heavy metal anomaly above ore in this area. To verify this absence of introduced ore stage heavy metals, site B was resampled on a closer grid (samples 20b, 21b, 22b, and 23b in Fig. 3) and the entire suite of 23 samples were re-analyzed by the field method. As an additional check, selected samples of the fresh and altered monzonite that showed comparatively wide variances in the amounts of heavy metals present were decomposed with a mixture of hydrofluoric and perchloric acids and

analyzed by Holmes' method (5). The field and laboratory check analyses confirmed the absence of a positive heavy metal anomaly and showed, conversely, the presence of a negative anomaly—an erratic impoverishment of zinc in the altered rock as compared with the relatively fresh monzonite at the fringe of the mineralized area.

TABLE 3.

RESULTS OF EXTRACTION OF HEAVY METALS FROM ALTERED INTRUSIVE MONZONITE ABOVE IRON BLOSSOM NO. 1 ORE BODIES.
(SITE B.)

| Sample no.[1] | Acetic acid-ammonium acetate extraction | | Sulfuric acid extraction | | | Alteration intensity |
|---|---|---|---|---|---|---|
| | Zn (ppm) | Pb (ppm) | Cu (ppm) | Zn (ppm) | Pb (ppm) | |
| 1b | 1 | 1 | 18 | 10 | 2 | Moderate |
| 2b | 1 | 1 | 16 | 4 | 0 | Intense |
| 3b | 1 | 1 | 8 | 0 | 0 | Intense |
| 4b | 1 | 1 | 18 | 2 | 0 | Intense |
| 5b | 2 | 1 | 150 | 60 | 0 | Moderate-low |
| 6b | 1 | 1 | 14 | 70 | 0 | Rel. low |
| 7b | 2 | 1 | 12 | 10 | 0 | Intense |
| 8b | 1 | 2 | 16 | 3 | 1 | Intense |
| 9b | 2 | 2 | 16 | 20 | 0 | Moderate |
| 10b | 1 | 1 | 16 | 20 | 0 | Moderate |
| 11b | 1 | 1 | 16 | 8 | 0 | Moderate |
| 12b | 1 | 1 | 18 | 60 | 10 | Low |
| 13b | 2 | 1 | 8 | 50 | 0 | Low |
| 13b′ | 2 | 1 | 14 | 4 | 0 | Intense |
| 14b | 2 | 1 | 8 | 1 | 0 | Intense |
| 15b | 1 | 1 | 16 | 2 | 0 | Intense |
| 16b | 2 | 1 | 8 | 1 | 0 | Intense |
| 17b | 2 | 1 | 14 | 4 | 0 | Intense |
| 18b | 2 | 1 | 8 | 2 | 0 | Intense |
| 19b | 2 | 1 | 16 | 20 | 12 | Low |
| 20b | 2 | 1 | 70 | 60 | 12 | Intense-moderate |
| 21b | 2 | 1 | 12 | 4 | 3 | Intense |
| 22b | 2 | 1 | 16 | 8 | 0 | Intense |
| 23b | 2 | 1 | 80 | 9 | 1 | Intense |
| 24b | 2 | 1 | 14 | 20 | 20 | Low |

[1] For location see Figure 3.

*Discussion.*—The problem of interpreting the results obtained at site B is then twofold:

1) Why is a positive geochemical anomaly absent in the altered rock above ore at this point?

2) What conditions attendant upon ore deposition would cause an *impoverishment* of zinc in the altered rock near ore?

To attempt to find an answer to these problems a comparative structural and petrographic re-examination of both areas was made. It was immediately evident that the two sites differed in important respects. At site A premetallization fissuring and brecciation extend into the extrusive rocks overlying the ore zone. This condition does not prevail at site B; there the ore bodies are overlain by unfractured yet similarly altered monzonite.

The relationship of the positive geochemical anomaly at site A to fracturing, brecciation, and alteration was clearly defined by a megascopic and petrographic study of the altered rock in that area. The latities and rhyolite at site A were exposed to four successive stages of alteration prior to ore deposition. This alteration has been described by Lovering et al. (11). The earliest alteration stage was characterized by solutions that introduced magnesium, formed chlorite at the expense of the mafic minerals of the igneous rock, and dolomitized the underlying limestones. An argillizing stage related to monzonite intrusion followed the chlorite stage. The sedimentary and igneous rocks were severely leached by acid solutions during this stage, and clay minerals were formed from constituents present in the lavas. The leaching action of the argillizing solutions resulted in a total porosity of 5 to nearly 40 percent in the igneous rocks and as much as 50 percent in the underlying dolomites. After a short interval these porous rocks were invaded by hydrogen sulfide emanations, which converted the indigenous magnetite of the lavas to pyrite. Silicifying solutions, which followed the argillizing and pyritizing solutions, changed some of the argillized rock to jasperoid and decreased the total porosity created during the argillic stage to approximately half its maximum value. In spite of this reduction in porosity the silicified rock still had an effective porosity many times greater than that of unaltered rock.

Intramineralization adjustment along the Sioux-Ajax fault reopened the solution channelways immediately before the ore stage and brecciated the jasperoid masses, further increasing their porosity and permeability and preparing them as loci for ore deposition. During the ore stage the metallic minerals invaded the silicified dolomite and limestone because of the greater porosity of the jasperoid, which was due both to brecciation and to previous argillic alteration. Neutralizing of the acid solutions by the dolomite within the jasperoid masses may have caused the deposition of ore. The near-spent ore solutions moved farther upward along the fault and also invaded the brecciated altered extrusive rocks above the main ore zone and there deposited minute amounts of metallic minerals. A positive geochemical anomaly was thus formed above the underlying ore.

Persistent fracturing does not extend into the igneous rock overlying the ore bodies at sampling site B, near the Iron Blossom No. 1 shaft. Study of thin sections of the altered monzonite from site B showed that, although pyritization and argillization are moderately strong, silicification is negligible. Movement along the comparatively minor fractures that later controlled ore emplacement apparently did not break through the monzonite and underlying latite tuffs and flows at the time of ore deposition owing to the absence of brittle jasperoid. Instead it feathered out in the clayey incompetent argillized rock and created impervious gougy zones. The altered monzonite at site B, lacking persistent hydrothermal channels in brecciated silicified zones, therefore acted as an effective dam for mineralizing solutions, and no positive geochemical halo was developed substantially above the ore. It is believed, however, that a positive halo may have been formed by diffusion of heavy metal ions in the igneous rock immediately above the ore-bearing fissures but that this halo is restricted to a narrow zone adjacent to the ore bodies.

NEGATIVE ANOMALIES RELATED TO PRE-ORE ALTERATION.

To investigate further the nature of the negative zinc anomaly in the altered rock at site B, samples of fresh and of moderately altered monzonite from the walls of veins that cut the Silver City monzonite stock 1½ to 2 miles southwest of the sampling sites were also collected and analyzed. The total copper, zinc, and lead content of these rocks was determined by laboratory procedure (5, 16), after the material was dissolved with a mixture of hydrofluoric and perchloric acids (Table 4).

TABLE 4.

TOTAL HEAVY METALS IN SELECTED SAMPLES OF CORRESPONDING FRESH AND ALTERED ROCKS.[1]

| Sample no. | Alteration type | Zinc (ppm) | Lead (ppm) | Copper (ppm) |
|---|---|---|---|---|
| [2] 12a | Moderately altered latite | 50 | 65 | 15 |
| 2a | Argillized, pyritized latite | 20 | 150 | 15 |
| [3] 13b | Unaltered monzonite | 120 | 25 | 20 |
| 13b′ | Argillized, pyritized monzonite | 30 | 50 | 30 |
| [4] 10d | Unaltered monzonite | 80 | 23 | 25 |
| 4d | Argillized, pyritized monzonite | 20 | 37 | 30 |
| [5] 8sbe | Unaltered monzonite | 120 | 9 | 35 |
| 2sbe | Argillized, pyritized monzonite | 28 | 30 | 35 |

[1] Analyzed by Holmes' method for total copper, lead, and zinc. Modified by using hydrofluoric acid and perchloric acid (5).
[2] Site A, Iron Blossom No. 3 shaft area.
[3] Site B, Iron Blossom No. 1 shaft area.
[4] Near Iron Duke shaft, Tintic district, Utah.
[5] Near Sunbeam shaft, Tintic district, Utah.

The altered rock has a definitely lower zinc content and a higher lead content than the unaltered rock. No fixed rule seems to account for the behavior of copper; it may, however, show a slight decrease in the altered rock. The three metals behave similarly in the oxidized outcrops of pyritic base metal veins, wherein zinc is totally removed and copper is only partly removed if a carbonate mineral is present. Lead is commonly enriched in such vein outcrops through the solution and removal of the gangue and the relatively more soluble metallic minerals. Almost completely oxidized pyrite is disseminated through the weakly argillized rock in each of the areas examined. It is believed that some of the zinc and perhaps a small amount of copper was removed by sulfuric acid generated on the oxidation of this pyrite at or near the surface.

Petrographic study, and bulk and powder density determinations correlated with the analyses of these and other samples indicated, however, that the acids formed on the weathering of pyrite did not selectively leach the rock sufficiently to account for the total removal of the zinc. Neither did it account for the presence of a comparatively large amount of lead that was assumed to have been residual in the weathered pyritic rock.

The petrographic study indicated also that in each area examined the altered rock had been argillized by early acid emanations and solutions, and the pheno-

crystic plagioclase and biotite had been converted chiefly to kaolinite, halloysite, sericite, and potash clay. The orthoclase (17) was resistant to attack by these acid solutions and therefore was but little altered. The increase in lead content suggested by the results presented in Table 4 may have been accomplished by argillizing solutions moving from zones of more intense alteration where lead was dissolved to zones of weaker alteration or to masses of previously altered rock where it was precipitated. The nonextractability of the introduced lead under the conditions of the field test suggests that the lead may have entered the lattice of the hydrothermal micas as they were formed and therefore is not extracted as readily as the ore stage metal, which is presumed to have been deposited in fractures as sulfides and subsequently oxidized.

The destruction of biotite and magnetite during argillic and pyritic alteration suggests that a substantial amount of zinc originally present in those minerals (1, 17) was removed by argillizing acid solutions prior to the introduction or the weathering of the pyrite.

The indigenous copper is surprisingly little affected by either hypogene or supergene leaching solutions. The syngenetic copper, like the lead, was probably not extracted because of its original form, it perhaps being present as submicroscopic sulfide particles (2, 3, 17) enclosed within the groundmass orthoclase and quartz (2, 13), the minerals most resistant to argillic alteration. The copper sulfides themselves are also comparatively insoluble in the weak acids characteristic of hydrothermal and supergene solutions.

Negative heavy metal anomalies are highly significant in the geochemical appraisal of possible hidden mineral deposits. The relatively low "background" amount of zinc that is present in the altered rock prior to the invasion of the ore solutions may permit the detection of minor secondary zinc introduction, even though the values may be less than the total zinc content that was originally present in the unaltered rock. The redeposition of lead in areas of low zinc content by the pre-ore argillizing solutions may give rise to erroneous positive predictions of concealed ore. This possibility of error need not be given serious attention, however, if low intensity extraction reagents and methods are used.

A most important aspect of the relation of severely argillized igneous rock to geochemical prospecting is that after even slight deformation the dense rock may dam off ascending metal-bearing solutions and prevent the formation of positive heavy metal anomalies over blind ore bodies. In this situation geochemical prospecting methods would be of doubtful value in determining the presence or absence of ore underlying areas of argillized rock altered by later pervasive solutions closer to the ore stage.

## CONCLUSIONS.

1. Positive geochemical anomalies delineate channels used by ore-depositing solutions. Where conditions of structure and alteration are favorable, they may directly overlie blind ore bodies.

2. These anomalies are localized by the structures and the alteration zones that control the occurrence of the associated ore deposits. Bedrock geochemi-

cal prospecting is, therefore, an additional method of determining which part of a favorable structure or alteration zone is likely to be ore bearing at depth.

3. Much of the original zinc may be flushed from igneous rocks by the acid solutions characteristic of argillic alteration, and a minor amount may be converted to the water-soluble sulfate by the acids generated from the weathering of pyrite and may be dissolved in meteoric waters.

4. Lead is less mobile than zinc in altering solutions; it appears to have been readily redeposited from argillizing solutions in irregular zones adjacent to masses of intensely altered rock.

5. Secondary heavy metal anomalies related to ore bodies at depth can be satisfactorily determined by partial extraction methods using sulfuric acid as an extractant.

U. S. GEOLOGICAL SURVEY,
BELTSVILLE, MD.,
AND
WASHINGTON, D. C.
*March 23, 1951.*

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# TEMPERATURES OF MINERAL FORMATION IN BOTTOM-RUN LEAD-ZINC DEPOSITS OF THE UPPER MISSISSIPPI VALLEY, AS INDICATED BY LIQUID INCLUSIONS.

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ABSTRACT.

The paper describes an investigation of liquid inclusions in sphalerite and calcite from bottom-run deposits of the Upper Mississippi Valley lead-zinc district. Suites of specimens from three deposits and scattered specimens from three additional deposits have been studied. Results indicate that sphalerite was deposited at temperatures (uncorrected for pressure) ranging from 121° C to 75° C. Calcite of types II and III, formed subsequently to sphalerite and representing the middle two stages of calcite formation in the deposits, formed at temperatures ranging from 50° to 78° C. Correction for pressure requires raising the values given by amounts estimated to range from 5° to 10° C.

The data obtained further suggest that in some deposits temperature declined progressively during sphalerite deposition but in others varied irregularly.

The results of the study are discussed with reference to the various assumptions upon which the use of liquid inclusions for determining temperatures of mineral formation is based. It is concluded that deposits of the Upper Mississippi Valley type are valid subjects for investigation by the liquid inclusion method. The results of the present study appear to be consistent with the geologic characteristics of the deposits.

The study indicates that conclusions as to temperatures of formation of minerals must be based on suites of specimens representative of the deposits involved, not on single specimens or crystals.

## INTRODUCTION.

THE use of liquid inclusions in crystals for determining temperatures of mineral deposition has received much attention in recent years. In this country, the revival of interest in a long-neglected technique is due largely to W. H. Newhouse, who studied liquid inclusions in sphalerite crystals. Studies by E. Ingerson, F. G. Smith, and others have followed, and temperature measurements for various minerals from a number of localities are now on record. Some of the data are in harmony with previous ideas of temperatures of mineral deposition, others are markedly at variance.

In most of the investigations thus far on record, the crystals used have been more or less isolated from their geologic contexts; i.e., temperature determinations have been correlated incompletely, or not at all, with mineral paragenesis. Few studies of temperature variation within single deposits or groups of deposits have been made. The geologic significance of many of the data obtained is therefore in doubt, and the role of temperature in the formation of the mineral deposits involved cannot be satisfactorily appraised. Fur-

thermore, the results of studies of liquid inclusions cannot be checked adequately against other geologic information.

The present investigation is an attempt to supply systematic data on temperature variations during deposition of the ores of certain Upper Mississippi Valley lead-zinc deposits. In order that the geologic significance of the results may be appraised, the study has been correlated with a parallel study, by M. H. Tupas, of mineral paragenesis and processes of mineralization in the district, and with findings of geologists of the U. S. Geological Survey. The data given represent about seven months of full-time work during the period September 1948 to January 1950. The data appear adequate to indicate some of the broader features of temperature conditions during mineralization. It is hoped that additional information will be obtained when mining developments in the district provide new opportunities for collecting materials. The present paper is essentially a progress report.

ACKNOWLEDGMENTS.

This work was made possible by a grant from the Wisconsin Alumni Research Foundation, and the support of the Foundation is gratefully acknowledged. Dr. Allen V. Heyl, Mr. Erwin J. Lyons, and Mr. Allen Agnew, geologists successively in charge of the field party of the U. S. Geological Survey that has been investigating the Upper Mississippi Valley lead-zinc area, have freely contributed information and guidance based on seven years of detailed studies in the area; the writers take pleasure in expressing their heavy indebtedness to these men. Dr. Mateo H. Tupas has furnished essential information on mineral paragenesis and has assisted in the collection and correlation of specimens from various deposits. The writers also wish to acknowledge the cooperation and many courtesies extended by the operators of the mines visited.

## LEAD-ZINC DEPOSITS OF THE UPPER MISSISSIPPI VALLEY.

*General Description.*—The Upper Mississippi Valley lead-zinc district is an area of about 1,800 square miles lying mostly in southwestern Wisconsin but extending into adjacent parts of Iowa and Illinois (Fig. 1). The district is underlain chiefly by Ordovician strata that have a gentle regional dip to the southwest. The deposits mined are mostly in the upper part of the Platteville formation and in the Decorah and Galena formations (Fig. 2). There are hundreds of deposits in the district; most of those productive in recent years are in Wisconsin, but there is an important group of mines in the area around Galena, Illinois.

The area and its deposits have been studied periodically since the 1840's, and the literature concerning them is voluminous. The reader is referred to the report by Bastin and others (2)[1] for a critical review of information then available. A paper by W. H. Newhouse (24) is especially pertinent to the present investigation. Newhouse studied liquid inclusions in sphalerite from the district and obtained temperature values of 80° to 105° C.

[1] Numbers in parentheses refer to Bibliography at end of paper.

Investigations of the U. S. Geological Survey and the Illinois Geological Survey since 1941 have greatly clarified the occurrence and structural characteristics of the deposits. The deposits are located along several sets of fractures and minor folds that are superimposed on the regional structure (*22*; 4, pp. 63–67). According to their stratigraphic position, two main groups of deposits are recognized: top-run and bottom-run. The stratigraphic relationships of these deposits are summarized in Figure 2. Top-run deposits are mostly fillings or linings of fractures or solution-widened fractures in the upper part of the Galena formation; the deposits consist largely of galena and

FIG. 1. Map showing the extent of the Upper Mississippi Valley lead-zinc district and the locations of mines from which samples have been collected for study. Adapted from Lyons, Heyl, and Agnew (1949).

iron sulfides. Representative material from these deposits is not available, hence they have not been studied by the writers. Bottom-run deposits (Fig. 3) are found in the lower part of the Galena formation, in the Decorah formation, and in the upper part of the Platteville formation. They include two major types: vein and disseminated deposits. Vein deposits are the more common; they are partly fillings of sub-horizontal bedding-plane fractures (flats), partly fillings of moderately to steeply dipping fractures (pitches) that cut across the beds. Pitches and flats occur in a wide range of combinations in various deposits. Disseminated deposits are formed by partial replacement of certain members of the stratigraphic sequence, notably the Guttenberg member (oil rock) of the Decorah formation and the Quimby's Mill member (glass rock) of the Platteville formation. Suites of samples from three accessible pitch-flat ore bodies (Andrews, Bautsch, Liberty), together with a smaller group of samples from one disseminated deposit (Little Grant),

have been investigated. Vein materials from the Crawford and Tennyson Mines have also been studied, but these latter mines are now closed, hence only scattered samples were available.

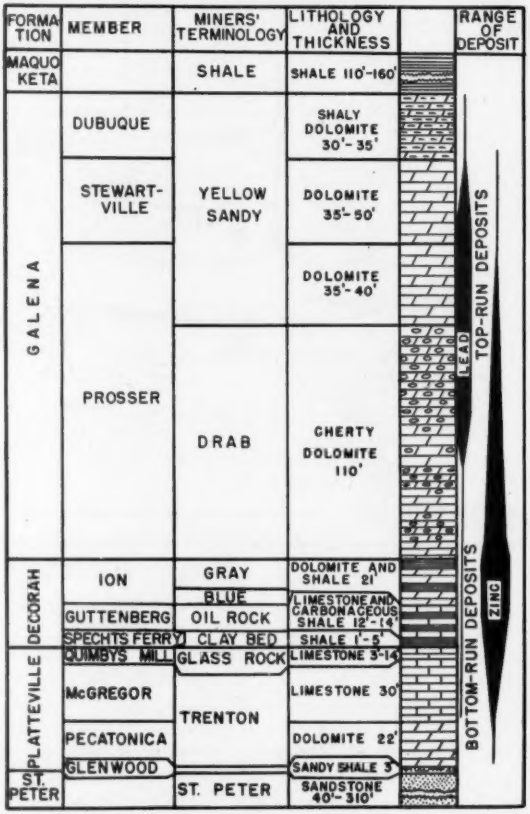


FIG. 2. Stratigraphic section for the Upper Mississippi Valley lead-zinc district, showing the stratigraphic range of lead and zinc deposits. After Lyons, Heyl, and Agnew (1949).

*Vein Ores.*—Vein ores are simple fissure fillings that commonly consist of successively deposited layers of ore and gangue minerals. The veins are symmetrically layered except where later minerals occur in fractures that cut earlier-formed layers or follow contacts between these layers and the vein walls. Many parts of the veins were incompletely filled, and these contain crystal-lined openings ranging from a quarter-inch to several feet in breadth

and from a few inches to tens of feet in length along dip or strike. Such cavities have furnished much useful material for the present work. M. H. Tupas (32) has shown that the sequence of mineral deposition is constant from deposit to deposit. The proportions of minerals vary from place to place, however, even within a single vein, and locally one or more members of the

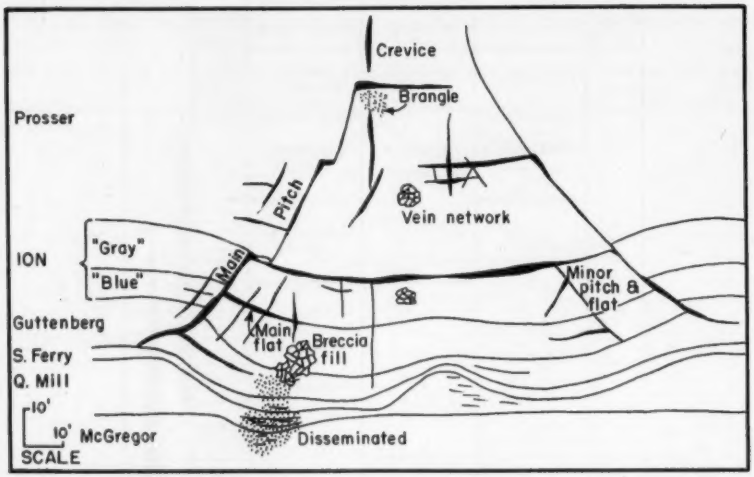


FIG. 3. Diagrammatic cross-section showing types of occurrence of ore in bottom-run deposits. Adapted from Willman, Reynolds, and Herbert (1946).

sequence are discontinuous or lacking. The sequence recognized by Tupas for fully developed veins is given in Figure 4.

The temperature data reported in this paper were obtained from liquid inclusions in sphalerite and calcite. In typical vein ore the sphalerite forms a layer a quarter of an inch to as much as six inches thick. This layer consists of sublayers of light-colored sphalerite alternating with thinner layers of dark brown sphalerite, as shown in Figure 5. Boundaries between light-colored sublayers and overlying dark brown sublayers are commonly gradational. Those between dark brown sublayers and overlying light-colored sublayers are commonly abrupt. In mine workings, the sublayers can be traced for tens of feet along dip or strike. Each sphalerite layer consists of tightly packed elongate crystals arranged perpendicular or subperpendicular to the inner[2] surface of the layer. Some crystals extend across the full width of the layer. Others terminate within it, but terminations show no systematic relation to boundaries between sublayers. Sphalerite layers are commonly gently undulating, owing to variations in their thickness and in the thickness of iron sulphides separating sphalerite from the vein walls.

[2] In the following discussion "inner" is used in the sense of location toward the center of a vein; "outer" means toward the vein walls.

The structure of the sphalerite, particularly the color banding, has been likened to colloform banding, and Behre (2, p. 115) regards the ores as colloidal precipitates that later crystallized. It has been suggested (3, p. 804; 2, p. 115) that the sphalerite was originally wurtzite. An analogy has been drawn between the sphalerite and the schalenblende of Aachen, ascribed by Ehrenburg (15) to colloidal deposition of zinc sulphide. Tupas, however, points out that certain features are difficult to explain if the layered sphalerite was originally deposited in colloidal form. First, the inner surfaces of sphal-

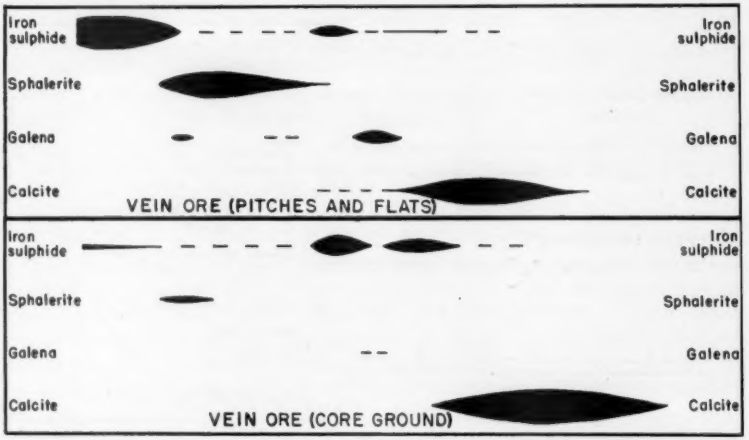


FIG. 4. Paragenetic sequence of minerals in bottom-run deposits, according to Tupas (1950).

erite layers are almost all rough surfaces defined by crystal faces. These faces are the terminations of the individual sphalerite blades. Iron sulphides deposited after sphalerite are molded around the crystal terminations. Smooth skins of the type that commonly bound the outer surfaces of colloidal precipitates (14, pp. 18–19) are very rare. Second, etched polished surfaces show that growth lines parallel to the terminal faces are common in sphalerite and that the crystals are polysynthetically twinned. The twin lamellae are parallel to the long dimensions of the crystals. Third, the color banding does not show the characteristics of rhythmic colloform banding. In most places it follows the growth zones and is angular in detail; it therefore appears to reflect variations in the composition of the ore-forming solutions. Less commonly the color banding is independent of growth zones, cutting across them. It is noteworthy that in disseminated ore similar relations are found in granular aggregates of sphalerite grains; apart from color banding this type of ore shows no textural characteristics suggestive of colloidal deposition. The origin of the color banding independent of growth zones is obscure; it may be due to diffusion of iron through sphalerite after crystallization.

Another significant feature is that the dark-brown sublayers of sphalerite consistently contain innumerable small cavities that are elongate parallel to the sublayers. The walls of the cavities transect the sphalerite blades and the twin lamellae within the blades, hence, the sphalerite must have been crystalline when the cavities were formed. The cavities appear to have been formed before deposition of the next overlying layers, hence, sphalerite must have attained the crystalline state at least within a very short time after it was deposited.

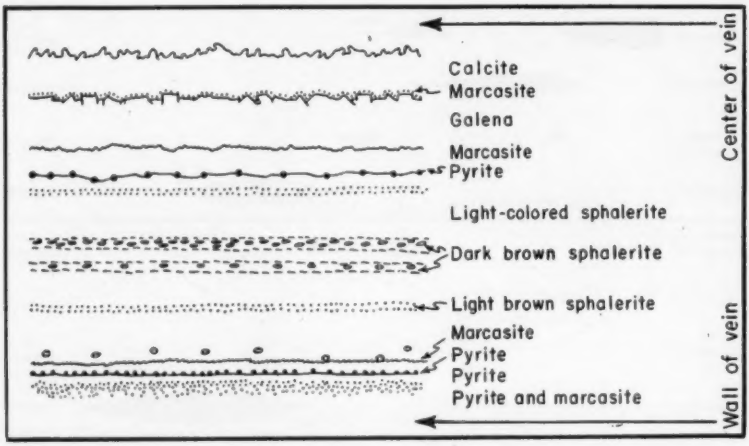


FIG. 5. Ideal section of one-half of a symmetrically banded vein as developed in bottom-run deposits. M. H. Tupas (1950).

The factors discussed above do not prove that sphalerite was deposited instantly in crystalline form, but they are consistent with this interpretation. There seem to be no sound reasons for ascribing the bulk of the sphalerite to colloidal precipitation. The writers, therefore, assume that the sphalerite was deposited in crystalline form and that the primary liquid inclusions present are a valid subject for temperature investigation. The temperature data obtained from sphalerite crystals of the various textural types present in the ore bear out the assumption. Data obtained for banded sphalerite are consistent with data obtained for unbanded sphalerite.

How much sphalerite was originally deposited as wurtzite is uncertain. Tupas points out that the dark-brown sphalerite has textural features approaching those described for wurtzite, but that the light-colored sphalerite, apart from its elongate habit, resembles ordinary sphalerite in texture and in internal structure as indicated by etching.

Calcite occurs as isolated crystals, clusters of crystals, and more or less continuous layers. The calcite shows a systematic variation in habit that is a striking feature of the district. Four types of calcite have been recognized by

A. V. Heyl (personal communication), and their sequence of deposition has been studied by Tupas. Type I consists of white, pink, or brownish cloudy calcite forming obtuse rhombohedra. Most of it is later than the bulk of the sulphides.

Type II occurs as sharp, scalenohedral, cloudy crystals on the earliest calcite. Calcite of this type was formed mostly after the fourth stage of deposition of iron sulphides, but in a few places the outer portions of the calcite layers contain inclusions of galena apparently formed at the same time. Type III occurs as clear overgrowths on Type II; crystals of Type III are sharp, clear scalenohedrons modified by rhombohedral faces. Type IV calcite consists of clear obtuse rhombohedrons, either alone or as overgrowths on Type II. Whether it was formed contemporaneously with Type III or later is not known. Marcasite occurs as inclusions in all types of calcite. Films of marcasite separating Type II from overgrowths of Type III are common.

*Disseminated Ore.*—Typical disseminated ore consists of crystals and crystal aggregates of sphalerite and pyrite, with or without galena, scattered in shale, limestone, or dolomite. Most of the sphalerite is light-colored and granular; isolated crystals are euhedral to subhedral. Some show growth lines when etched in polished surface. Color banding related to grain boundaries, crystallographic directions, or outlines of aggregates of crystals is present. A small proportion of the sphalerite, dark brown in color, has an etch-structure suggesting that it may originally have been wurtzite. According to Tupas this type occurs only as discontinuous layers resting on light-colored sphalerite. The layers have formed by cavity filling.

Paragenetic relationships in disseminated ores are difficult to determine, but Tupas reports that the sequence is broadly similar to that for vein ores.

*Relation of Mineralization to Structural Development of the Bottom-Run Deposits.*—As suggested by Figure 3, two broad structural units can be recognized in the fully developed vein-type bottom-run deposits. The outer unit consists of the outer pitches and flats. The inner unit, commonly designated the "core ground," consists of inner pitches and flats, and mineralized breccia and solution cavity fillings (brangle), in the ground between the main pitches. The order of mineralization of these two portions of an ideally developed deposit is still being debated. A. V. Heyl (personal communication) has concluded that mineralization spread from the pitches into the core ground, and M. H. Tupas' studies have led him to the same conclusion. According to Tupas, however, structural development of the bottom-run deposits was essentially complete by the end of sphalerite deposition, although reopening of some of the fractures took place after the sphalerite stage and prior to deposition of iron sulphides, galena, and calcite.

## PROCEDURE.

Suites of minerals were collected from three mines in the area, the Liberty, Bautsch, and Andrews Mines (Fig. 1). In each mine an attempt was made to obtain representative samples from all the structural types in which the ore occurs (pitches, flats, core ground, etc.) and throughout the available hori-

zontal and vertical range of the ore. Variations in the ore itself, such as color, crystal habit, and type of banding, were noted and correlated, where possible, with structure and position in the paragenetic sequence. These details are discussed more fully and correlated with the temperature studies in a later section of this paper. Scattered specimens from three other mines that are closed and therefore inaccessible were also assembled from various sources.

Three minerals, sphalerite, calcite, and barite, were chosen for temperature studies. Sections about 0.2 mm thick were cut from selected specimens of each and given a high polish with a superfine abrasive (American Optical Co. M–304) on a muslin-covered lap. This technique proved satisfactory for sphalerite. Calcite and barite treated in this manner, however, were damaged by the jarring of the grinding and polishing laps. Liquid inclusions in these minerals leaked when heated; hence all specimens had to be ground and polished by hand on glass. Leakage of inclusions in sphalerite also was anticipated, and to prevent this a number of the sphalerite sections were enclosed in thin blocks of transparent Castolite set at a low temperature (60° C). This safeguard proved unnecessary, however, as later experiments with unenclosed sphalerite sections showed no leakage at all up to 15° C above the temperature of vacuole disappearance.

The sections were heated in a simple cell set on the microscope stage. The cell contains an aluminum ring that is one-half inch thick, has an inside diameter of two inches, and is three-quarters of an inch in height. A small nichrome resistance wire coiled around the outside of the aluminum ring heats the interior of the cell by conduction through the aluminum. The temperature is controlled by a variable resistance coil. An insulating asbestos board cover fits over and around the cell, providing space for mica windows at the top and bottom. No medium other than air is used, hence the top of a mineral section must be highly polished for clear vision. Preliminary tests of the cell showed that convection currents were set up between the aluminum ring and the mica at the top. These currents were eliminated and a constant temperature attained throughout the cell by placing a copper plate below the upper mica window. The copper plate has a narrow slit for observation. A smaller cell to eliminate convection currents entirely has since been constructed.

The section to be examined was set on a wire stand inside the cell and observed while the temperature of the cell was gradually increased. A magnification of 420 × was used. In all sections the absence of liquid carbon dioxide was determined at the outset by heating the inclusions slightly over 31° C, the critical temperature of carbon dioxide, and looking for increases in the sizes of the vacuoles or bubbles contained within the liquid inclusions. No such increases were noted, hence liquid $CO_2$ is probably not present in appreciable amounts. The sizes of the bubbles within the inclusions were also examined to detect leakage of liquid from the inclusions. Sections showing abnormally large bubbles, indicating leakage prior to heating, were not used. To avoid the effects of leakage during heating those inclusions suspected of having the lowest temperatures of bubble disappearance were measured first, i.e., those near the outer edge of a crystal or near the center of a symmetrical

vein. Temperatures of bubble disappearance were measured by a small thermocouple inserted through the side of the cell and brought in contact with the base of the section. It was found that many inclusions in calcite leaked when the temperature was raised beyond the point of bubble disappearance. Inclusions in sphalerite, however, commonly would stand a considerable overshoot without leakage. Leakage during heating was recognized by a sudden increase in size of the bubble or by failure to return to original size on cooling. Sections in which leakage occurred were discarded as untrustworthy for further study.

## RESULTS.

*General Statement.*—Results of measurements of the temperatures of bubble disappearance in sphalerite and calcite are given in Table 1. No data are given for barite. All barite specimens obtainable have a finely bladed structure that makes preparation of thin slices extremely difficult. Most of the specimens are weathered. Slices have been prepared from barite from three localities but are unsuitable for temperature studies. They contain only elongate inclusions that show widely varying vacuole-cavity ratios. The inclusions are apparently secondary and had leaked prior to examination. All data for calcite are for crystals of Types II and III.

TABLE 1.

| Mine | Mineral type | Temp. range (in ° C)* |
|---|---|---|
| Bautsch | vein sphalerite | 75–110 |
| | brangle sphalerite | 79–95 and 90–121 |
| | vein calcite, crystals | 50–51 |
| Andrews | vein sphalerite | 76–103 |
| | knob sphalerite | 85–99 |
| | vein calcite, massive | 71 |
| Liberty | vein sphalerite | 75–93 |
| | knob sphalerite | 77–91 |
| | vein calcite, crystals | 50–63 |
| Little Grant | sphalerite, crystal | 83–103 |
| | calcite, crystals | 72–77 |
| | vein calcite, massive | 61–73 |
| Crawford | vein sphalerite, crystals | 80–92 |
| | vein calcite, crystal | 72–77 |
| Tennyson | vein sphalerite | 75–84 |
| | vein calcite, massive | 78 |

* No pressure correction has been applied to these values. To allow for pressure the values probably should be increased by amounts on the order of 5° to 10° C.

If the data for the six mines are grouped, the total temperature ranges become:

| | |
|---|---|
| For sphalerite | 75°–121° C. |
| For calcite (Types II and III) | 50°–78° C. |

*Liberty Mine.*—Two groups of specimens were collected from the Liberty mine. One consists of specimens taken at intervals along an irregular line ex-

tending north-south across the ore body. The specimens are from small pitches and flats at various places across the base of the ore body and from similar pitches and flats at various levels above the base. The collection represents a vertical stratigraphic range of about 45 feet, from the oil rock to the lower part of the lower Galena, and a horizontal distance of about 200 feet east-west along the strike. The second group consists of specimens taken along the north edge of the ore body to a point about 150 feet east of the first

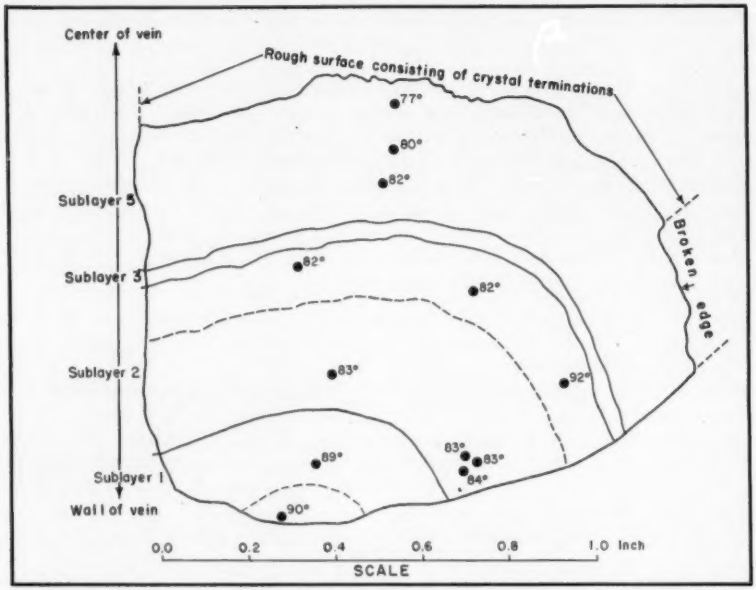


FIG. 6. Sketch of section of sphalerite layer, specimen W–L–4, Liberty Mine, showing locations (heavy dots) of liquid inclusions for which temperatures of bubble disappearance (figures beside dots) have been determined. Sublayer 4 of the sequence characteristic of the sphalerite of the Liberty Mine is lacking in the specimen.

group. All specimens consist of typical layered sphalerite terminated inward by crystal faces. In many places, the sphalerite layers are covered by calcite crystals. Some of the vein material consists of hemispherical knobs of layered sphalerite likewise terminating inward in crystal faces.

Temperatures of bubble disappearance were determined for 107 liquid inclusions in 8 sections of sphalerite. Most of the sections show an orderly variation in temperatures of bubble disappearance. Temperatures range from a minimum of 75° C for inclusions at the inner edges of sphalerite layers to a maximum of 93° C for inclusions next to the vein walls (Fig. 6). Normal vein ore and knobby vein ore give similar values, and no large variations have

been noted between specimens. No relation between temperatures of disappearance and stratigraphic position, location within the ore body, type of ore, or type of structure localizing the ore is indicated. The readings for the mine as a whole are in the lower part of the range indicated for the group of mines studied.

Liquid inclusions in general appear to be more common in the lighter-colored sublayers, but the difficulty of detecting inclusions in the darker sublayers may account for this in part. The number of inclusions in any given sublayer varies from specimen to specimen, falling to zero in some specimens. Temperature values for particular sublayers vary slightly from section to section, but a systematic decline in values inward from the vein walls is found in most of the sections. This is illustrated in the following table:

TABLE 2

| Specimen | Sublayer 1 (outermost) | Sublayer 2 | Sublayer 3 | Sublayer 4 | Sublayer 5 (innermost) |
|---|---|---|---|---|---|
| W–L–4 | 89°–90° | 83°–84° (92°) | 82° | Lacking | 77°–82° |
| W–L–11 | 90° | No inclusions | 87° | Lacking | 82°–88° |
| W–L–7 | 83°–87° | 83°–88° | 84° | 82°–87° | Lacking |

In the specimens listed, a general decline in temperature values inward is shown. The variations from sample to sample for particular sublayers exceed the experimental error. In some specimens values for adjacent sublayers overlap one another by amounts that also exceed the experimental error. This error is small, for inclusions within very thin sublayers commonly give values differing from one another by not more than $\pm 1°$ C. This figure agrees well with the expected error as determined from calibration data and experiments in rate of heating.

A few inclusions giving anomalous temperature readings occur in most sphalerite sections. Some of the inclusions are located in or near healed cracks and appear to be secondary. One section from the core ground, consisting of sphalerite lenses in a calcite matrix, contains nothing but secondary inclusions. Other inclusions giving anomalous readings occur in altered areas and near later sulphides. These readings are all recorded in our results, but have been disregarded in establishing primary temperatures. Still a third group of anomalous values has been obtained, however, from scattered inclusions, at least one or two per section. These inclusions give readings as much as 10°–15° C higher than the readings given by neighboring inclusions of the same sublayers (Fig. 6, and Table 2, sublayer 2). The inclusions are quite normal in all other respects. They are negative crystals that, so far as can be determined in sections, are well removed from sulphides or cracks. No gas content has been noted, nor are the bubble-cavity ratios noticeably abnormal. A very few inclusions giving low values have also been noticed.

The data for calcite crystals from the Liberty Mine are not as complete as for sphalerite. The inclusions consist of negative crystals and irregularly shaped cavities, both occurring mainly in broad growth lines parallel to the

external crystal faces. The inclusions tend to leak when heated, hence only a few could be measured in each section. Temperature variations within sections could not be determined. The best readings obtained range from 50° C. to 63° C. This range of values is based on temperature measurements of 14 liquid inclusions. It probably is not the total range of temperatures over which calcite was deposited, but it is consistent with the sequence of mineralization established by Heyl and Tupas (32), who regard calcite as later than sphalerite.

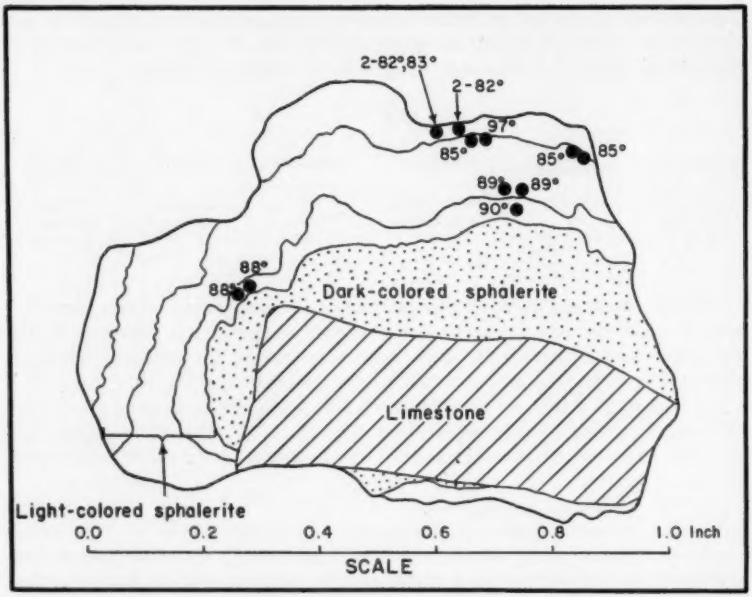


FIG. 7. Sketch of section of sphalerite nearly enclosing a fragment of limestone. Heavy dots show locations of liquid inclusions for which temperatures of bubble disappearance (adjacent figures) have been determined. Brangle ore, Bautsch Mine.

*Bautsch Mine.*—All samples from the Bautsch Mine are from the south end. They cover a horizontal range of about 100 feet and a vertical range of 35 feet, from the upper part of the Lower Chert to the lower part of the Blue. One sample is from the edge of the ore body, whereas the remainder are from the interior. Pitch-flat and brangle vein ores are both represented. Brangle is the miner's term for the crystals of iron sulphide, sphalerite, calcite, and galena which are found together in breccia and solution cavity fillings. Structurally, brangle is vein ore; the same sequence of sublayers in the sphalerite can be recognized as in pitch-flat veins.

Eighteen sections of sphalerite (cut from 11 specimens) and 2 sections of calcite have been studied. Temperatures of disappearance for 99 primary inclusions in the sphalerite sections have been measured. In general these sections show the same characteristics as those from the Liberty Mine (Fig. 7). The temperature values show a less orderly variation from the vein walls inward, however, and the number of anomalous, yet apparently primary, inclusions is considerably greater. One sample (Fig. 8), shows a variation pattern that is not only irregular, but markedly at variance with patterns for other

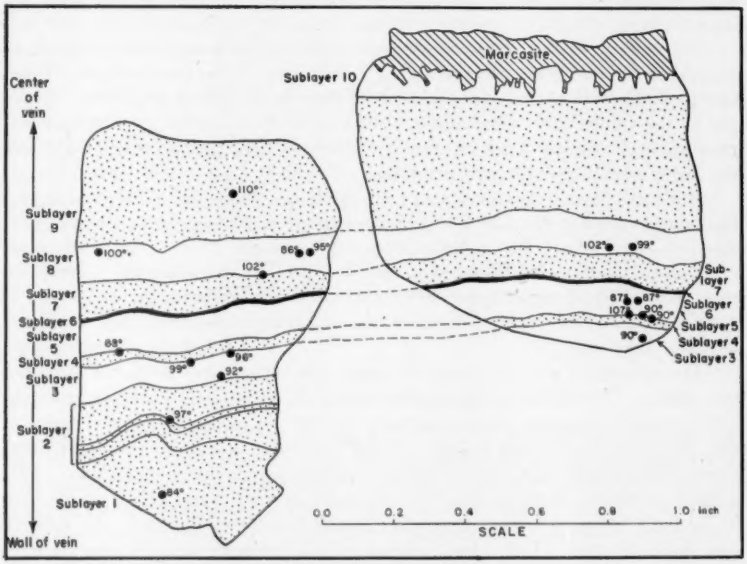


FIG. 8. Sketch of two sections from a single specimen of banded sphalerite, vein ore, Bautsch Mine. The two sections cover all but the innermost .2 inch of the sphalerite layer. Locations of liquid inclusions and temperatures of bubble disappearance are indicated as in Figures 6 and 7. Darker sublayers of sphalerite are stippled; lighter-colored sublayers are blank.

specimens. The highest temperature value is given by an inclusion near the inner edge of the sphalerite layer, the lowest by an inclusion near the outer edge of the sphalerite layer.

As in the Liberty Mine, no systematic variation of temperature with structure, texture, or stratigraphic position has been found in the Bautsch Mine. Pitch-flat ore and brangle ore give similar temperature patterns. A sample from the edge of the ore body, at a point stratigraphically higher than any other sample studied, actually gives temperature values for the outermost sublayer that are higher than those given by any other samples. However, this particular sublayer is present only in two other sections and the values for the re-

maining, more common sublayers are in agreement, hence the difference for the outermost sublayer is regarded as no more significant than the variation between sections from the Liberty Mine. Sections from the Bautsch Mine show comparable variations. The overall temperature range of 75°–121° C indicated for the sphalerite from the Bautsch Mine is more significant. The lower limit is the same as for the Liberty Mine, but the upper limit is much higher. A number of readings in different sections confirm this high maximum. Some of the values given by sublayers 1 and 2 exceed the highest values obtained for any of the other mines studied, anomalous inclusions excepted.

The calcite crystals collected from the Bautsch Mine and studied are all associated with, and later than, the brangle sphalerite in the core ground. Leakage in these sections has made comprehensive data difficult to obtain. Judging by the values from other mines, values of 50–51° C given by 4 primary inclusions in 2 sections of calcite from the Bautsch Mine probably represent only the lower part of the temperature range.

*Andrews Mine.*—Samples from the Andrews Mine were collected over a horizontal range of 250 feet and a vertical range of 20 feet, and represent both the outer pitch-flat veins and the inner core ground. Six sections of sphalerite and 2 sections of calcite were studied for liquid inclusions. Temperatures of bubble disappearance were measured for 49 primary inclusions in sphalerite, but temperature values could be obtained for only 3 primary inclusions in calcite.

The sphalerite sections show the same general features as in the previous two mines. Temperature values obtained show an orderly decrease from the walls inward, but each section contains several apparently primary inclusions that give anomalous high values. Outer pitch-flat veins and inner pitch-flat veins (core-ground ore) gave similar readings for primary inclusions. Secondary inclusions were prominent in the core-ground material but uncommon in the outer veins, a feature that was noticed to a lesser extent in the Liberty and Bautsch ores. Individual sublayers of sphalerite were found to give broadly similar temperatures throughout the ore body, though there are minor variations. The sphalerite ore is unusually thick in the Andrews Mine; some symmetrical veins are 9–12 inches thick. No relation, however, between thickness and temperature of formation is indicated by values given by the liquid inclusions. No values for sublayer *a* were obtained, but values for sublayer *b* together with the overall range 75–103° C obtained for the sphalerite place the Andrews between the Liberty and Bautsch Mines in temperature of formation. The constancy of the lower limit of 75°–76° C in these three mines is striking. Vein calcite from the core ground and cutting the sphalerite gave temperature values of 71° C.

*Other Mines.*—Scattered specimens were obtained from four inoperative mines in the district, the Little Grant, Crawford, Tennyson, and Gray Mines. As representative suites were not available, the temperature data are of limited value, but their agreement with those obtained for the Bautsch, Liberty, and Andrews Mines is of considerable interest.

The Little Grant Mine is a disseminated deposit with crystals of sphalerite and galena partly replacing the Guttenberg member of the Decorah formation. Calcite occurs in veins cutting the ore. The liquid inclusions in sphalerite gave values between 83° and 103° C, showing that the range for disseminated deposits is not markedly different from that for vein deposits. This is important since it confirms the conclusion that the finely layered, color-banded vein ores are valid subjects for temperature study by the liquid inclusion method and that the development of cross-cutting color bands has not introduced major errors into the results. Calcite from the Little Grant proved tougher than that from other mines, and it was possible to heat and examine numerous inclusions without loss of liquid. Fourteen inclusions from vein calcite cutting the sphalerite gave values of 61–73° C. In a section made from a crystal of calcite, over 70 inclusions in several growth bands gave readings in the range 72–77° C.

One section of vein sphalerite and calcite from the Crawford Mine near Hazel Green, Wisconsin, yielded temperature values of 80–92° C for the sphalerite and 72–77° C for calcite resting on the sphalerite.

A section of reopened vein from the middle run of the Tennyson Mine gave results ranging from 75° to 84° C for sphalerite and a value of 78° C for calcite cutting sphalerite.

Several sections of calcite were prepared from a large zoned crystal from the Gray Mine. Values of 60–65° C were obtained from intermediate growth bands before leakage occurred.

## APPRAISAL OF RESULTS.

*General Statement.*—The use of liquid inclusions for determining temperatures of mineral deposition has been widely debated during the last few years, particularly since publication of Ingerson's analysis (19), and there are strong differences of opinion. It is generally recognized that the method, if sound, has great potential value, for it offers hope that the absolute values of temperatures of deposition can be closely approximated for a wide range of minerals. It is far from certain, however, that the method is universally applicable to mineral deposits, or even to a major share of them. With each presentation of new data, therefore, the method must be reappraised, the theory underlying it reviewed, and a decision made as to whether the deposits and minerals under investigation satisfy the requirements of the theory.

*Theory of the Use of Liquid Inclusions.*—Liquid inclusions were apparently first noticed by Sir David Brewster (7, 8), but it was H. C. Sorby (31) who suggested that liquid inclusions in a crystal are portions of the original mother liquor included during crystallization, and that they may be used to indicate the temperature of formation. He reasoned that as the mineral cooled from its crystallization point the liquid contracted much more than its solid host, leaving a vacuole or bubble within the inclusion. Then if the ratio of bubble to inclusion size were measured, and the composition and compressibility of the liquid were known, the temperature at which the bubble would disappear if reheated could be calculated. This would be the temperature of

formation, neglecting pressure. Since Sorby's time the method has been simplified by use of heating cells that permit the observer to watch the disappearance of the bubble. Holden (17), Newhouse (24), Twenhofel (33), and Ingerson (19) have been prominent in furthering this work and advancing the theory. Recently Scott (28) and Smith (29) have introduced a technique for recording the decrepitation of the inclusions when crushed crystals are heated.

The theory in its present form involves the following basic assumptions:

(1) The liquid completely filled its cavity at the time of crystallization.

(2) Primary liquid inclusions can be distinguished from secondary inclusions.

(3) The liquid is an aqueous solution containing no carbon dioxide or other gas in large concentration.

(4) The pressure on the liquid at the time of inclusion was small, or its magnitude can be estimated.

(5) There has been no significant change in the volume of the cavity itself due to pressure, solution, or precipitation.

(6) There has been no addition of liquid to the cavity or loss of liquid from it.

(7) Representative samples are used for temperature determinations.

In general it has been agreed that if these assumptions are satisfied the method is valid and the temperature of bubble disappearance approximates the actual temperature of formation. For minerals formed under pressure, a correction must be added to compensate for compression of the liquid at the time it was included. Ingerson (19) gave a set of curves for estimating this correction and Kennedy (20) has since given a revision of these curves. Dreyer, Garrels, and Howland (13, p. 34) have suggested, however, that in any system of relatively poor circulation (such as a vein), thermal effects due to exothermic reactions or to heat of crystallization might raise the temperature of formation of crystals above the temperature of the major portion of the solvent. They further suggest, therefore, that the liquid inclusion method, after pertinent pressure corrections, may give only the temperature of the solution at the surface of the crystallizing material and that the general temperature of the mineralizing solutions may be much lower. W. S. Twenhofel (personal communication) reports that studies of liquid inclusions in various synthetic crystals at the Naval Research Laboratory during World War II gave temperature values that checked very closely with directly measured temperatures of formation. More recently, P. A. Peach (25) has reported that liquid inclusions in halite crystals grown in a simple aqueous solution disappear at temperatures closely approximating the actual temperature of formation. Neither of these laboratory investigations, however, fully meets the objections raised by Dreyer and his colleagues. At the Naval Research Laboratory, the mother solutions were agitated steadily during growth of the crystals. The conditions under which Peach grew halite crystals are not described, but even if these were grown in a simple solution not mechanically agitated, one may assume a certain amount of convection. Furthermore, there are no exothermic reactions in a simple aqueous solution; only the heat of crystallization

is available for raising the temperature. The objections of Dreyer and his colleagues therefore appear to merit thorough consideration, entirely apart from the particular case of halite cited in their paper.

*Sources of Error.*—It is evident that there are numerous possible sources of error in the method. Quite apart from possible exothermic effects, the method fails to give the true temperature of formation if any one of the basic assumptions cited above is not satisfied. Inasmuch as mineral deposition is known to take place under a wide range of conditions, the validity of the assumptions involved must be appraised for each deposit or group of deposits studied.

Some of the basic assumptions can be made for the Upper Mississippi Valley lead-zinc deposits with considerable confidence. First, the probability that cavities in the crystals were completely filled with liquid is strong. The deposits belong to a group that by all geologic indications was formed at temperatures well below the critical temperature of pure water; moreover, the available data (23) suggest that the solutions were moderately concentrated and would therefore have critical temperatures appreciably higher than that of pure water. Second, in most of the crystals studied, primary liquid inclusions are readily recognized from their distribution with respect to growth zones and other primary internal structures. Later secondary inclusions are present in many crystals but are confined to areas near healed fractures and to areas adjacent to later sulphides. Third, geologic evidence indicates that the deposits were formed at depths probably not greater than 2,000 feet from the surface, hence, the pressure correction required should be no more than 5° to 10° C, even if pressure is taken as due to the weight of overlying rocks instead of the hydrostatic head. Fourth, the samples studied were selected to represent the full range of types of ores present at each of the four deposits and are known to include the types most characteristic of these deposits.

In part, the assumption with regard to volume changes can also be made with some assurance. Ingerson (19, p. 376) has shown that the compressibility of quartz is so low compared to that of water that changes in the volumes of cavities containing aqueous inclusions would be negligible, even with initial pressures up to 2,000 atmospheres. Inasmuch as the compressibilities of sphalerite and calcite (5, pp. 51, 53, 54, 55) are only about half that of quartz, volume changes in these minerals should be even less significant as sources of error. Possible errors due to changes in solubility of sphalerite and calcite with changing temperature are less easy to evaluate. Such changes might cause solution of cavity walls or precipitation of solute, which would alter the ratios of cavity volumes to volumes of liquid. The concentration, and therefore the compressibility, of the liquid would likewise be changed. The solubility of calcite (Handbook of Chemistry and Physics, 1947, p. 391) at 75° C is .0018 gram per 100 cc of water; at 25° C the solubility is .0014 gram. The solubility of zinc sulphide is in dispute, but all data given indicate that its solubility in pure water at low or moderate temperatures is extremely small. Verhoogen (34, pp. 775–777) has calculated the solubility at 100° C as $2 \times 10^{-4}$ grams per 100 cc of water and the solubility at 25° C as $3 \times 10^{-6}$ grams per 100 cc.

These solubility data suggest that solution of cavity walls with changing temperature is not a major source of error. As the compositions of the liquid inclusions are not known, however, we do not know whether solubility data for sphalerite and calcite in water can be used to predict solubility changes with cooling of the liquid inclusions. This is particularly true because the concentrations of $CO_2$ and $H_2S$, which appreciably affect calcite and sphalerite solubilities, are not known, except that the low ratios of bubble volumes to cavity volumes at room temperature and the steady shrinkage of the bubbles as temperature is raised suggest that the concentrations of the two gases are low. All we can say is that only a very remarkable change in the solubilities of the two minerals with temperature would introduce significant errors into the data.

The question of precipitation of solute on cooling of these inclusions is equally difficult. The composition and concentration of the included liquid are major features. Newhouse (23) found mainly NaCl with minor $CaCl_2$ in liquid inclusions of sphalerite and galena crystals from the Tri-State deposits. He estimated the concentration of sodium chloride as 12–25 grams per 100 cc of water. The few available analyses of liquid inclusions in other localities (summarized by Newhouse, 23), suggest that the most common dissolved substances are the chlorides and sulphates of sodium, calcium, and potassium. Many of these analyses are old and, hence, not as accurate as modern analyses; moreover, the proportion of primary to secondary inclusions represented is not known. The general pattern, however, seems established. Ions of the common ore and rock-forming minerals are conspicuously absent, or present in minute amounts. This would indicate that such ions either were not included as a rule or were precipitated in solid form after inclusion.

The pattern of the solubility data cited above suggests that if zinc and sulphide ions were present in solution in sphalerite inclusions and calcium and carbonate ions present in calcite inclusions, sphalerite and calcite would tend to precipitate on cooling. But the amount of either mineral precipitated would be so small, assuming moderate initial concentration rather than supersaturation, that errors introduced into the temperature values would be negligible. Greater precipitation, on the other hand, might be expected for the soluble salts commonly found by analysis in liquid inclusions. Solubility data indicate that saturated solutions of chlorides and sulphates of sodium, calcium, and potassium are likely to yield precipitates, of halite and sylvite especially, when cooled. Halite (Lange's Handbook of Chemistry, 1946, p. 1233) has a solubility of 39.8 grams per 100 cc. of water at 100° C and of 36.0 grams at 20° C, an appreciable difference. Actually, tiny cubes have been noted in many inclusions in crystals of granitic, metamorphic, and hydrothermal rocks and are generally regarded as precipitated cubes of halite. The analyses suggest that potassium is not as common as sodium in inclusions, but given the same initial degree of saturation, potassium chloride (sylvite) is even more likely to precipitate on cooling than sodium chloride. Sylvite (Lange's Handbook of Chemistry, 1946, p. 1231) has a solubility of 56.7 grams in 100 cc of water at 100° C as compared to 34.0 grams at 20° C. Bowen (6) suggests that some of the cubes reported as halite may actually be sylvite. Newhouse, however, was unable to find any precipitated material in the many inclusions he ex-

amined from the Tri-State deposits. The present writers likewise failed to detect any precipitated material in the inclusions of the Upper Mississippi Valley deposits. The inference is that the solutions were unsaturated with respect to the chlorides.

The nature of the cavities occupied by liquid inclusions in sphalerite also has a bearing upon the problem of precipitation of solute. Most of the inclusions are fillings of essentially tetrahedral negative crystals. Negative crystals are reported to form from original irregular cavities by precipitation of the solute from liquid inclusions and its deposition on the walls under crystallographic control of the host. Negative crystals are also reported to form during crystal growth, however, owing to local irregularities in deposition along specific crystallographic directions. Experimental evidence (35, 12) indicates that crystals grow by the addition of small crystal blocks or aggregates of atoms or ions rather than individual atoms or ions. Layers then spread out laterally from these nuclei, often meeting in slightly irregular boundaries. Adjacent blocks or layers with slightly different orientations or with irregularly abutting surfaces or corners result in lineage structures that might provide the necessary geometric cavities for negative crystals. Buerger (9, 10) and Newhouse (23) report abundant negative crystals along such lineage boundaries in crystals of galena and sphalerite from the Tri-State deposits. Bunn and Emmett (12) show photographs of regular-sided pits developed on flat crystal surfaces during growth. The pits are due to encirclement of certain areas by spreading layer fronts. Primary negative crystals, therefore, do exist.

The distinction of primary negative crystals from those due to precipitation of solute during cooling is probably possible only in rare instances where the linings are visible. Lindgren (21) described transparent linings on the walls of liquid inclusions in quartz of the granite and veins of the Clifton-Morenci copper district of Arizona. Linings were not recognizable as such in the sphalerite inclusions studied by the writers. Many were extremely dark in color, but this can be attributed to total reflection of light from the cavity faces. The solubility data given above, moreover, indicate that sphalerite contained in solution in inclusions would be insufficient to form linings of any size unless the liquid were greatly supersaturated when included. This seems unlikely, for the liquid most apt to be included would be immediately adjacent to and intermixed with the growing surface; i.e., the very liquid that is creating the surface by precipitation. This liquid should be nearly in equilibrium with the crystal. As the degree of saturation or supersaturation of a liquid is known to vary along a growing surface (11), it is reasonable to suppose that inclusions may also vary in concentration, perhaps reaching supersaturation in rare instances. Precipitation of solute from an inclusion of considerable concentration would reduce the volume of the cavity. In general, it would also decrease the volume of the liquid, but to a lesser degree. This would result in a small relative increase in total volume of liquid and would tend to give a temperature of bubble disappearance slightly lower than the temperature of crystal formation. In the present study, however, most of the anomalous values obtained were high rather than low. Negative crystals did not

give lower values than irregular inclusions from the same zone. From this fact, together with the apparent lack of precipitated material, we conclude that precipitation within inclusions is not a major source of error in the temperature values obtained in the present study.

There are other grounds, however, for believing that changes in cavity volume and in concentration of solutions are unimportant. The inclusions are very small; hence for any given inclusion the ratio of surface to volume is high. With the slow rate of heating employed in the temperature determination, it seems probable that the inclusions will react with the walls so that at the instant of disappearance of a bubble, the inclusions should be nearly or actually as concentrated as at the time of formation.

The final assumption to be considered is the one requiring that no liquid be added to the cavity or subtracted from it since its formation. There are at least two mechanisms by which loss or addition of liquid might take place. One is leakage or infiltration of liquid along cracks, cleavage surfaces, or lineage boundaries. This has undoubtedly happened to many inclusions, but the effects are hardly likely to be uniform from inclusion to inclusion within a single crystal. If a group of inclusions gives consistent results, therefore, most workers have assumed that neither leakage nor infiltration is involved.

Changes in the amount or composition of liquid in an inclusion might also take place by diffusion of ions through the host, either into the inclusion or outward from it. Diffusion of ions through crystal lattices is well established. It is conceded a definite role in metasomatism (18), and Barth (1) and others have even suggested that in petrogenesis it may operate on a regional scale. The occurrence, in some of the sphalerite aggregates studied, of dark brown color bands unrelated to growth lines suggests that diffusion of iron may have taken place after crystallization, and that liquid inclusions may have been changed in volume or concentration. The possible effects of this cannot be appraised at present. The limited range of temperature values obtained suggests, however, that the process, if operative in the lead-zinc deposits, has been remarkably uniform in its effects, not only from part to part of the same deposit, but from deposit to deposit. No correlation between temperature values obtained and presence or absence of color bands has been observed.

Recently Kennedy (20) has questioned the validity of assuming that uniform vacuole sizes signify the absence of any change in volume of the liquid. He notes that some liquid inclusion work has given results which are low according to present geologic criteria. Low results might be accounted for by the movement of liquid into vacuoles as a result of differential pressures set up after contraction of the primary liquid of the vacuoles on cooling. Thus, uniform vacuole sizes over a wide area might only mean that the area had spent a long period of time at one temperature and pressure, during which time a balance between external and internal pressure had been achieved. Kennedy cites the results of a few experiments to show that vacuole sizes are decreased by application of water pressure to samples of fluorite.

Certainly this is a serious criticism of one of the basic assumptions of the method and, if true on a large scale, would mean that temperatures of vacuole disappearance could only give at best a lower limit to the true temperature of formation. Smith et al. (30), in reply, state that bubble sizes are not uni-

form in much of the Precambrian of Canada but give systematic areal patterns that can be contoured, suggesting that change in liquid volume is not significant in some of the oldest rocks on record. No simple relation of degree of filling to depth below the present surface has been found. The present writers would like to see the results of further controlled experiments before making a final appraisal of Kennedy's criticism. It is most unlikely, however, that ambient pressure would be a large factor in affecting inclusions in minerals formed in open channels at shallow depths, as were the ores of the Upper Mississippi Valley. Consistency of results here should be an index of their reliability.

The objections of Dreyer, Garrels, and Howland (13) next require consideration. The objections are serious, for a full answer requires knowledge of exothermic reactions involved in mineral deposition, of rates of crystallization, and of rates of heat transfer from the faces of the growing crystals. Only a qualitative answer based on geologic probabilities is possible for any group of deposits. The objections would appear to be most serious for deposits formed at depth by replacement, in rocks in which the channels of mineralization are small, tortuous, and perhaps poorly connected. In such deposits, circulation is probably sluggish and rates of heat transfer are probably low. Conversely, the objections appear least serious for deposits formed in or along open fissures at shallow depths, where circulation should be relatively active and heat transfer relatively rapid. Obviously, however, no clearcut comparisons can be made. Much would depend on relative rates of reaction and crystallization, which would determine the rate at which heat is released.

The deposits of the Upper Mississippi Valley belong to the second group. The pitches and flats were obviously open channels during much of the mineralization epoch. Some channels were filled by the close of sphalerite deposition but many were still incompletely filled at the close of mineralization. Rates of circulation and consequently of heat transfer must have varied from place to place, and even from time to time at a given place. It is quite possible that some of the differences in temperatures of deposition indicated by inclusions in adjacent sublayers of sphalerite are due to this cause. If so, the more limited range of temperature indicated for calcite would suggest that heat transfer was more effective than at the sphalerite stage.

The considerations discussed above indicate that there are several uncertainties involved in interpreting the temperature data, because the sources of error cannot all be evaluated accurately. Uniform readings of a group of inclusions within a crystal have commonly been taken as strong evidence that the temperature data give true values of temperature of formation. It is still possible, however, that the readings may be in error by some common factor, hence we doubt that liquid inclusions in any single specimen can be taken to indicate the overall temperature of mineralizing solutions. With increase in the number of specimens and in the horizontal and vertical range that they represent within a deposit, uniform results for a particular mineral species become correspondingly more reliable. If a large number of specimens from localities well spread over a deposit or a group of deposits is studied, it seems unlikely that all readings will be incorrect by some common factor due to variations in rate of heat transfer or to diffusion in the solid. For the deposits

under consideration, the number of specimens studied would appear to eliminate the possibility that the readings as a whole are in serious error due to these two causes. Errors having other sources may be involved, but for reasons given above, we conclude that these errors are of secondary importance.

*Geologic Appraisal.*—Until the soundness of the liquid inclusion method is more securely established, all temperature data for groups of deposits must be appraised in the light of ordinary geologic data. Discrepancies are to be expected, inasmuch as the data of geologic thermometry from other sources are far from satisfactory, but results completely at variance with geologic experience require rigorous testing before acceptance. Recent literature contains several noteworthy discrepancies. Calcite, commonly considered to be the last mineral to form in lead-zinc ores of the Tri-State district, is reported to have formed at 222° C (28, p. 644), whereas the previously deposited sphalerite is reported to have formed at temperatures of 90° to 135° C (24, p. 748). Quartz in pegmatites is reported to have formed at the relatively low temperatures of 175° to 250° C (19, p. 387), whereas a number of minerals in the hydrothermal range are reported as formed at comparable or much higher temperatures. For example, quartz in the mesothermal veins of Butte is reported to have formed at 300° to about 380° C (27, p. 28), fluorite from the mesothermal deposits of Luna County, New Mexico, is reported to have formed at temperatures ranging from 202° C to 150° C (33), and pyrite in the hypothermal deposits of the McIntyre mine is reported to have formed at temperatures as high as 630° C (29, p. 633). Must current concepts of temperature ranges of mineral deposition be revised, or are the discrepancies due to deficiencies in sampling or in methods or techniques of temperature measurement used?

For the deposits under discussion, the temperature values obtained by study of liquid inclusions appear consistent with geologic characteristics. The mineral assemblage present in the Upper Mississippi Valley deposits, the textural and structural features of the ores, and the geologic history of the region suggest deposition at shallow depths and at low temperatures. Further than this, no conclusions appear warranted. It is generally assumed that the earlier-formed minerals of a hydrothermal deposit are deposited at the more elevated temperatures, but this is yet to be proved. The orderly decrease in temperature during sphalerite deposition suggested by the present studies for the Liberty and Andrews Mines is therefore not evidence that the results are sound, particularly as it is not yet certain that the deposits of the Upper Mississippi Valley are hydrothermal in the ordinary sense.

## CONCLUSIONS.

From the results of the present study and the foregoing appraisal, we conclude that the liquid inclusion method is valid provided that it is applied with care to deposits that satisfy the assumptions on which it is based. The lead-zinc deposits of the upper Mississippi Valley appear to be one appropriate type, indeed they appear exceptionally favorable to this type of study. No first order errors are expectable, and the agreement of results with other geologic data suggests that second-order errors are at a minimum.

The bottom-run lead-zinc ores studied were deposited from warm rather than cold solutions. There is no direct evidence to indicate whether the solutions were strictly hydrothermal or were merely heated surface waters. Ignoring a pressure correction of perhaps 5° to 10° C, the sphalerite was deposited within the temperature range 121° C–75° C. The temperature of initial deposition varied from deposit to deposit studied, reaching a maximum at the Bautsch Mine, but the lower limit of temperature of sphalerite deposition was strikingly uniform at 75°–76° C. The upper temperature limit for calcite was the same as the lower limit for sphalerite. The lower limit indicated for calcite is about 50° C. The data for calcite, however, are limited; moreover, readings have been obtained only for calcite of Types II and III. The total range of temperature during deposition of calcite may have been broader. The data for calcite and sphalerite are consistent with the standard assumption that temperature decreases during mineralization. For sphalerite from the deposits of the Tri-State district, Newhouse (24) obtained temperature values from 135° C to 90° C by study of liquid inclusions. His results are in harmony with those of the present study, for the Tri-State ores have generally been regarded as formed within a somewhat higher temperature range than the deposits of the upper Mississippi Valley. Newhouse also studied a few specimens from the Upper Mississippi Valley ores and obtained temperature values of 80–105° C for sphalerite from Hazel Green, Wisconsin. This compares well with the values of 80–92° C obtained in the present study from a single section of sphalerite from the Crawford Mine at Hazel Green. However, Newhouse found no indication of orderly decrease in temperature during deposition of single crystals from the Tri-State district. He states that all the bubbles within one section disappeared at about the same temperature.

The temperature range given above for bottom-run deposits covers the main stages of deposition of the ores, but the earliest stage (pyrite and marcasite) and the latest stage (Type IV calcite) are not represented.

Within single deposits, temperature values obtained suggest no influence of structure or stratigraphic position on temperatures of deposition. The minor variations found within individual sublayers of sphalerite probably mean that the actual temperatures of the solutions varied slightly from point to point.

If the color of sphalerite is an adequate index of composition, the alternation of light and dark sublayers indicates that decline in temperature was not a controlling influence on the type of sphalerite deposited. It is possible, however, that the termination of the sphalerite stage and the onset of calcite deposition were influenced or even controlled by decline in temperature.

The anomalous values occasionally obtained in the present study emphasize that no single inclusion or single specimen should be relied upon to give representative temperature values. Samples for temperature studies must give adequate geologic coverage of a deposit.

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*April 9, 1951.*

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# PARAGENESIS OF THE TRI-STATE JASPEROID.

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ABSTRACT.

The characteristic gangue of the zinc ores of the Tri-State district and northern Arkansas, locally termed jasperoid, is believed by some geologists to be older than the sulphides and to have been extensively replaced by them. Others believe there has been no replacement of the jasperoid and that jasperoid and sulphides were deposited contemporaneously. New microscopic evidences of replacement of jasperoid by sphalerite and other sulphides are presented.

THE local name jasperoid has long been applied to a dense dark-gray to black chert that is a common gangue material in the zinc ores of the Tri-State district and of northern Arkansas. It is generally agreed to have been deposited by the replacement of sediments, largely limestone and dolomite. It is microcrystalline and composed mainly of quartz. In places it contains, as minor components, replacement remnants of the original sediments notably calcite, dolomite and glauconite. Less commonly adularia is present. Analysis shows the presence of organic matter, probably a residuum from the original sediments and to this the dark color of the jasperoid is attributed.[1] The microscopic appearance of the jasperoid has been well illustrated by McKnight.[2] On a smaller scale its xenomorphic crystalline character is shown in Figure 1 of the present article.

Jasperoid although commonly a component of the ores in the heavily mineralized portions of the Tri-State and northern Arkansas districts may be absent from the peripheral areas of lighter mineralization as at Alba, Missouri, where sphalerite is a direct replacement of limestone or dolomite. Further, jasperoid is not characteristic of the zinc and lead ores of other districts of the Mississippi Valley area. It is to be regarded, therefore, as a local rather than a general feature of the Mississippi Valley mineralization.

The position of the jasperoid in the paragenetic sequence of the ore minerals has been discussed of recent years by McKnight,[3] by Bastin and Ridge,[4] and by Lyden.[5] Paragenetic diagrams are given by Bastin and Ridge (p. 110) and McKnight's paragenetic conclusions are summarized (p. 111). The

[1] Ridge, John D., The genesis of the Tri-State zinc and lead ores: ECON. GEOL., vol. 31, pp. 298–299, 1936.

[2] McKnight, Edwin T., Zinc and lead deposits of northern Arkansas: U. S. Geol. Survey Bull. 853, Pls. 10 and 11, 1935.

[3] Idem, pp. 118–123.

[4] Bastin, E. S., and Ridge, John D., in Contributions to a knowledge of the lead and zinc deposits of the Mississippi Valley region: Geol. Soc. America Spec. Paper No. 24, pp. 105–112, 1939.

[5] Lyden, Joseph P., Aspects of structure and mineralization used as guides in the development of the Pitcher Field: Mining Engineering, vol. 187, pp. 1251–1259, 1950.

conclusions of Bastin and Ridge are broadly accordant with those of McKnight especially in regarding the jasperoid as older than the main sulphide mineralization.

Lyden has had unparalleled opportunities to study the Tri-State ores and his descriptions and illustrations give a clear and convincing picture of their salient structural features. In a concluding section Lyden gives a paragenetic diagram for the ores of the Pitcher field (Fig. 8, p. 1259) and states: "The writer believes that the dolomite, jasperoid, sphalerite and galena were deposited contemporaneously and that the sphalerite did not replace the jasperoid." He proceeds to give his reasons for this conclusion some of which will be referred to later. While McKnight, Bastin and Ridge regard the later dolomite and the bulk of the sulphides as either contemporaneous or considerably overlapping they believe that these minerals are later than the jasperoid and have replaced it. The most appropriate defence of their conclusions lies in the presentation of new evidence which is the purpose of this paper.

The earlier paragenetic studies of Bastin and Ridge were made at the University of Chicago with the aid of the binocular microscope on specimens collected in the field especially for such studies. New studies with the aid of both binocular and compound microscope have been made by Bastin on Tri-State ores in the collections of Cornell University.[6] The results, which are here reported, appear to afford valid evidence that sphalerite was deposited on a large scale by the replacement of jasperoid and was also deposited as linings of cavities in the jasperoid. They also afford instructive examples of somewhat unusual replacement textures.

One of the most characteristic features of the Tri-State ores is the presence of automorphic crystals of sphalerite in a jasperoid matrix. Though utterly different in origin such ores resemble a porphyry in texture except that there is no uniformity in size among the sphalerite crystals and a single sphalerite area may be made up of several crystals instead of one. Such phenocryst-like areas of sphalerite in jasperoid as seen between crossed nicols under the petrographic microscope are shown in Figures 1 and 2. Of prime significance is the very great difference in grain size between the sphalerite and the jasperoid quartz. Some of the sphalerite crystals are 10 mm across, others are less than 1 mm. In a specimen from K bed in the Big Chief mine, Oklahoma, some crystals of sphalerite in the jasperoid are 1 cm across. In contrast to these the quartz crystals in the jasperoid range from .01 to .02 mm across. In other words the sphalerite grains are 50 to 1,000 times the size of the jasperoid quartz grains. Such great disparity in grain size is believed to imply a notable difference in the conditions and hence in the time of deposition.[7] The principle involved is the same as for a porphyry in which the conditions of formation are interpreted to have been different for the phenocrysts and for the matrix. The sphalerite and jasperoid are believed therefore *not* to be contemporaneous. Sphalerite is not the only sulphide in this ore that shows similar relations. A few small pyrite grains occur and show

[6] Most of the specimens are from a collection of carefully labelled ores donated to the University by George M. Fowler of Joplin, Mo.

[7] Bastin, Edson S., Interpretation of ore textures: Geol. Soc. America Mem. 45, p. 52 and Pl. 9, Fig. 2, 1950.

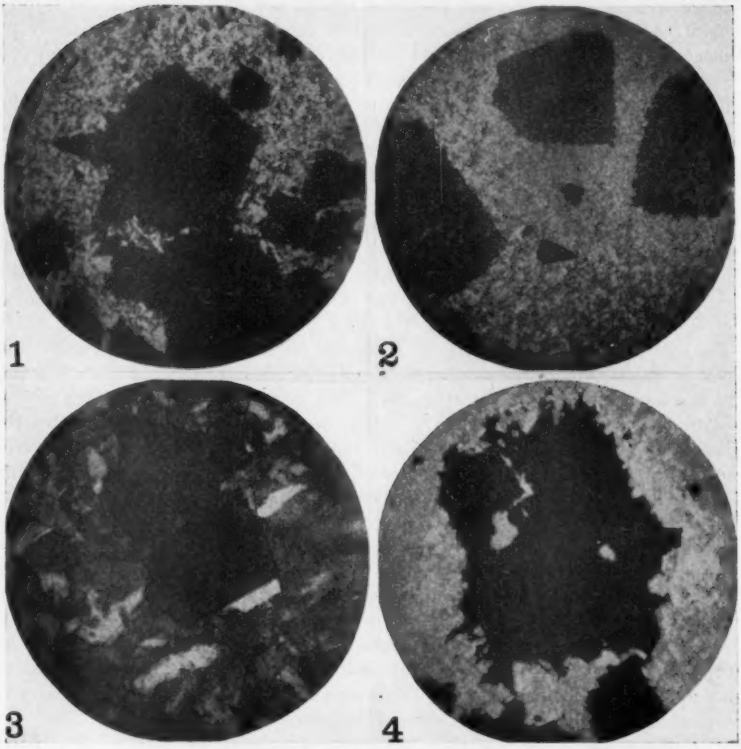
cubical outlines and smooth faces against the jasperoid. Its faces transect the boundaries of several grains of jasperoid quartz. In the specimen from the Big Chief mine, already referred to, a crystal of pyrite 3 cm across shows automorphic outlines against jasperoid.

There are other reasons also for believing that the sphalerite and the jasperoid are not contemporaneous. If they had been deposited concurrently we should expect to find jasperoid well within the sphalerite crystals. As shown in the illustrations this is not the case. Jasperoid occurs only at or near the peripheries of the sphalerite crystals.

If, as appears from the above relations, the sphalerite and the jasperoid are not contemporaneous two alternatives remain. 1) Sphalerite was deposited first (by replacement of limestone or dolomite) and jasperoid was then deposited around it, or 2) the limestone or dolomite was first replaced by jasperoid and the latter then automorphically replaced by sphalerite. Opposed to the first alternative is the fact that small cavities, seen under the binocular microscope to be fairly numerous in the jasperoid, are commonly lined with sphalerite which is therefore the younger of the two minerals. In some vugs jasperoid quartz grades into coarser gray quartz along the walls and this in turn is capped by sphalerite. Quartz was never observed capping the sphalerite in vugs. The sphalerite filling vugs is identical in appearance with that which forms automorphic crystals within the jasperoid and continuity between them is often observable.

The remaining alternative is that the sphalerite is younger than the jasperoid and was deposited mainly by jasperoid replacement but subordinately in cavities in the jasperoid. This interpretation is supported by the broadly automorphic outlines of most of the sphalerite against jasperoid illustrated in Figures 1 and 2. Further, as shown in Figure 3, some of the smaller sphalerite areas under high magnification show straight automorphic boundaries that transect the quartz grains of the jasperoid. Further, relatively small outlying areas of sphalerite are common well within the jasperoid as shown in Figures 1 and 2, while outliers of jasperoid well within the sphalerite do not occur. From this it is inferred that sphalerite developed at the expense of jasperoid rather than the reverse.

While most of the textural features point to the conclusion that the sphalerite has replaced and also lined cavities in the jasperoid, one textural feature, not yet considered, might be interpreted as indicating that the sphalerite and jasperoid are contemporaneous. This feature is shown in all of the figures except Figure 3. It consists in the fact that, although in a broad way the sphalerite shows automorphic outlines against jasperoid, yet when viewed in detail most of its boundaries are irregular due to an interlocking with jasperoid quartz. In some places as shown in Figure 3 such interlocking is absent. These relations are best seen in the unusually "ragged" edged sphalerite area shown in Figure 4. They have been interperted by Lyden (p. 1258) as indicating that sphalerite and jasperoid are contemporaneous. Especially at the top of Figure 4 some quartz can be seen to show its own crystal outlines against sphalerite.




FIGS. 1 and 2. Areas of sphalerite (dark) of broadly automorphic outlines in jasperoid, showing typical texture of jasperoid. × 23, Crossed Nicols.

FIG. 3. Automorphic crystals of sphalerite (black) in jasperoid. Note that several sphalerite crystal faces are straight and sharply transect grains of jasperoid quartz. × 50, Crossed Nicols.

FIG. 4. Unusually irregular sphalerite area (black) in jasperoid. Smooth gray areas in sphalerite are cavities; mottled gray is jasperoid. Especially at top and bottom note irregular tongue-like penetrations of jasperoid by sphalerite. At top and right some of the quartz grains possess automorphic outlines. × 23, Nicols 20 deg. off crossed position.

(All illustrations are from thin sections of ore from G bed in the Goodwin mine, Oklahoma.)

Contemporaneity is not the only possible interpretation of the marginal intergrowths of sphalerite and jasperoid quartz nor is it, in the writer's judgment, the true one. Geologists, including the writer, commonly classify replacements as pseudomorphic and automorphic. The form of pseudomorphic replacements is controlled by textural features of the replaced material—the host. Automorphic replacements assume their own characteristic crystal outlines. The contrast is illustrated in Plate 9 of the writer's book on Ore Textures [8] in which replacement veins controlled by galena cleavages are contrasted with cubical crystals of pyrite in a schist. But classifications are made by man for his own convenience and sooner or later Nature, recognizing no boundaries, comes forward with some intermediate occurrence to confound him. The classification may still have value as expressing the usual relations but the bare fact is that in some cases a replacement may be both pseudomorphic and automorphic even in the same microscopic field. The relation of sphalerite to jasperoid in the Tri-State ores seems to be a case in point. The sphalerite assumes *broadly* automorphic outlines but the microscope shows that in *detail* most of the sphalerite boundaries are irregular. Figure 4 seems to furnish the key to this irregularity. The upper and lower portions of this figure in particular show that the sphalerite at its peripheries penetrates the jasperoid by replacement in irregular tongue-like prongs. Sphalerite seems to have replaced smaller quartz grains first, the larger quartz grains resisting longest but eventually yielding for there are no quartz remnants in the interiors of the sphalerite areas. In contrast, a few sphalerite crystals in jasperoid, as shown in Figure 3, have smooth borders transecting the grains of jasperoid quartz. Also in the same specimen occasional grains of pyrite, which has a stronger tendency to assume automorphic outlines in replacement, *always* show sharp crystal faces that transect the jasperoid grains. Further, where, as in some of the Tri-State ores, sphalerite crystals have developed by replacement of limestone or dolomite instead of jasperoid the sphalerite faces are smooth rather than ragged. This contrast is attributed to a more ready replacement of the carbonates than of jasperoid quartz.

Perhaps the most plausible argument advanced by Lyden (p. 1258) against the replacement of jasperoid by sphalerite is the fact that the older cherts although also silica have not been replaced by sphalerite. Whether it is true without exception that the sphalerite never replaces the older chert it is certainly close enough to the truth to demand explanation. An alternative to Lyden's explanation was suggested by Bastin and Ridge in 1939 (p. 109) as follows: "While the jasperoid was susceptible to replacement by sulphides it is notable that the chert was almost immune. Only where fossils within the chert had been replaced by comparatively coarse quartz was this in turn replaced by sulphides. This contrast seems to indicate a textural control in replacement since chemically the chert and the jasperoid are similar."

In the writer's judgment the rarity of chert replacement cannot nullify the many evidences that have been given that jasperoid has been replaced by sphalerite and on a large scale. Rather, some other explanation for it must be sought. Although it is well known that replacement is often very sensitive

[8] Idem, pp. 34–42 and Pl. 9, Figs. 2 and 3.

to slight differences in the texture and composition of the host it is a difficult matter to place the responsibility with certainty upon specific differences. All that seems possible in the present case is to point out some contrasts between the chert and the jasperoid which may have protected the former against replacement. First as to the jasperoid, it is much coarser grained than the chert and contains numerous pores many of which have been lined with sphalerite. It is in many cases notably impure from the presence of inclusions of dolomite and potash feldspar as pointed out by McKnight (Pl. 11, Figs. A and B) for the northern Arkansas area. The cherts of the Tri-State district have been studied microscopically by Agar [9] and have been analyzed by Gregory.[10] Agar gives several photomicrographs of the cherts at approximately the same magnifications as Figures 1, 2 and 4 of the present paper. Agar's illustrations show that the cherts are much finer grained than the jasperoid. Microscopic measurements by Bastin on chert powders from four samples of Tri-State cherts show that the grain size is of the order of 0.02 mm or finer, whereas the larger grains of the jasperoid may reach ten times this size. Many of the cherts are surprisingly pure, five analyses by Gregory showing from 98.60 to 99.12% $SiO_2$. The superior fineness, compactness and purity of the chert seem to the writer to afford a reasonable explanation for its superior resistance to sulphide replacement.

ITHACA, NEW YORK,
*April 18, 1951.*

[9] Fowler, G. M., Lyden, J. P., Gregory, F. E., and Agar, Wm. M., Chertification in the Tri-State mining district: Am. Inst. Min. Met. Eng. Tech. Pub. 532, pp. 43–50, 1934.
[10] Idem, p. 35.

# REVIEWS

**Differentiation in Lavas of the Keweenawan Series and the Origin of the Copper Deposits of Michigan.** By HENRY R. CORNWALL. Geological Society of America, Volume 62, pp. 159–202, February 1951.

**Differentiation in Magmas of the Keweenawan Series.** By HENRY R. CORNWALL. Journal of Geology, Volume 59, pp. 151–172, March 1951.

Readers of Henry R. Cornwall's paper [1] on the metallic minerals in the Keweenawan lavas will profit by reading two companion papers by the same author in other journals. The three articles together provide an enlightening picture of the process of differentiation of the flows.

Economic geologists will be especially interested in the proposed answer to the century-old question: What is the source of the copper in the Lake Superior deposits? The author, believing that the copper came from the flows themselves, takes issue with the conclusions of Professional Paper 144 and reverts in some respects but with definitely original aspects to the views of Lane and his predecessors.

Chief among the reasons for this belief are: (1) computations from analyses of differentiated and undifferentiated flows indicate that the lava contained sufficient copper to account for the known mineralization; (2) analyses of successively consolidated fractions indicate that copper became concentrated in the liquid fraction late in the differentiation but was lost before the final solid fraction froze; (3) copper, some in sulphide and some in native form, occurs in the flows; part of this, at least, is held to be syngenetic.

Actually the number of samples used in computing the tenor of millions of tons of flow rock is far short of the number that would be demanded for estimating the grade of comparable masses of material if dollars and cents were involved, yet it is true that the analyses, so far as they go, give reasonably consistent results. But to prove that the ore *could* have come from the flows is one thing and to prove that it *did* is something else. In fact the papers show, very impressively, that the process of differentiation in individual flows was essentially duplicated on a grander scale in the parent magma. Thus the Duluth gabbro, or the magma that it represents, can still stand as a potential source of the copper.

But the author does not believe that it *was* the actual source, for reasons that go back to the old and puzzling question of why the copper is in native rather than sulphide form. The thesis is that in lavas sulphur boils off leaving too little to combine with whatever copper is present, whereas in intrusives such as the Duluth gabbro, which were emplaced at greater depth, the sulphur is retained and the copper fails to "go native." This hypothesis is not to be dismissed lightly as it may explain why small amounts of native copper are common in basalts the world over. But do we know enough about the quantitative aspects of the process to insist that copper occurring in native form could not have come from an intrusive?

In any case the author feels obliged to fall back on hydrothermal solutions (presumably from a deep magmatic source) because the present distribution of the cop-

[1] Cornwall, Henry R., Ilmenite, magnetite, hematite, and copper in lavas of the Keweenawan series: ECON. GEOL., vol. 46, pp. 51–67, 1951.

per does not accord with simple derivation from individual flows. But these solutions are denied their traditional source of metal—the magma—and assigned the task of collecting it from its first site of deposition in amygdaloids and sediments in order to redistribute it in the present bodies. Thus we come full circle back to a modified form of lateral secretion. As to the chemistry of the process the papers are reticent, perhaps discretely so, as the transportation of copper, except perhaps as salts of strong acids, presents a problem under any hypothesis. The association of native copper with iron which is now in the ferrous state but was formerly in the ferric condition is not without exceptions, but by and large it is so consistent and impressive that some genetic relation between bleaching of ferric minerals and deposition of native copper seems inescapable. The chemistry of Professional Paper 144 is still a reasonably satisfactory way of explaining this association though the complete disappearance of the resulting sulphates has always called for at least a mustard seed of faith. Until the chemistry and mechanism of the proposed lateral secretion are further clarified, geologists will do well to cling, at least with one hand, to the simpler concept of straight hydrothermal origin while recognizing that the same process, on a small and local scale, can go on within individual flows.

In focussing on the copper problem the reviewer has of necessity given short shrift to the main theme of the papers—the excellent discussions of the petrography, petrology, and differentiation of the lava flows. These are required reading for anyone interested in igneous rocks.

H. E. McKINSTRY.

**Triassic to Tertiary Stratigraphy Near Cerro de Pasco, Peru.** By WILLIAM F. JENKS. Geological Society of America Bulletin, Volume 62, pp. 202–220, 1951.

The region surrounding the ore deposits at Cerro de Pasco, Peru, has been studied by a series of mining geologists for more than thirty years but the emphasis, apart from the ores themselves, has naturally been on rock structure and intrusions rather than on stratigraphy. While the general sequence of formations has long been reasonably clear, thanks partly to the magnificent exposures on the high pampa, the study of the stratigraphy of the region recently published by William F. Jenks has served not only to clarify the dating of the rocks that constitute the sedimentary series but also to trace the history of sedimentation in its relation to deformation and erosion. To economic geologists one feature that stands out impressively in the history as well as in the structure of the region is the Cerro de Pasco fault. This fault, definitely traceable for five miles and probably extending much farther, passes through the midst of the great group of ore bodies and must have been important in localizing them. Its long history—it has been active repeatedly since Laramide orogeny—is most impressive.

H. E. McKINSTRY.

**Die nutzbaren Gesteine der Schweiz, 2nd edit.** By F. DE QUERVAIN AND M. GESCHWIND. Pp. 284; figs. 57. Kuemmerly & Frey, Bern, 1949. Price, Swiss Frs. 22.

Switzerland is known for its dearth of raw materials which must, however, not be confused with a lack of economic minerals. Like many midwestern states it has a wealth of industrial minerals.

This noteworthy book, which translated into English means "Economic Rocks of Switzerland," is the result of a long felt need for revision of the first edition which has long been out of print. The book deals with building stone, sand and

gravel, cement, clay, abrasives, and fertilizers. Especially noteworthy are the chapters on building stone. De Quervain has had particular experience with this type of material in his capacity as director of the testing division (Geotechnische Pruefstelle) of the Mineralogic-Petrographic Institute of the Eidgenoessische Technische Hochschule.

The book is intended as a reference work for economic geologists, petrographers and the stone trade of Switzerland. Each chapter dealing with a specific type of material is treated from the geographic, geologic and petrographic point of view. Mining methods and properties are likewise discussed. Reproductions of thin sections are given as well as a bibliography and references to the relevant geologic maps.

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CINCINNATI 21, OHIO,
*May 28, 1951.*

**The New Physics.** By SIR C. V. RAMAN. Pp. 144. Philosophical Library, New York, 1951. Price, $3.75.

Everyone will welcome such a book as this written by one of the world's half-a-dozen front-rank physicists. It is beautifully written in lucid and readable form that will delight and fascinate the student and the layman. The material was originally delivered as a series of radio talks to the Indian public and is therefore primarily intended for the layman. It brings better understanding to water, soil, weather, electricity, crystals, and familiar everyday phenomena. The chapters deal with shells, light and color in nature, science and industry, soil, water, weather, atmospheric electricity, crystals, cosmic rays, and the stellar universe.

**Guide to Geologic Literature.** By RICHARD M. PEARL. Pp. 239. McGraw-Hill Book Co., Inc., New York, 1951. Price, $3.75.

This unusual book will be welcomed by all followers of geology. It informs the reader of the various kinds of geologic literature and gives keys to locating books, maps, periodicals, abstract journals, index guides, bibliographies, public documents, newspaper articles, and unpublished theses. It really is a guidebook to the extensive world literature. It gives references to lists, indexes, and bibliographies that cover all published literature on geology from the earliest dates to the present.

Part I states the problem of geologic literature and how to conduct the search. Part II deals with library facilities and services. Part III treats of the kinds of geologic literature such as periodicals, abstracts, government documents, books, maps, etc. The book is designed to serve the history-minded student and the practicing geologist. It is prepared from the geologist's viewpoint rather than that of the librarian. It will be in continuous use by all geologists.

**Dating the Past—An Introduction to Geochronology, 2nd Edit.** By FREDERICK E. ZEUNER. Pp. 474; figs. 101; tbls. 62; pls. 24. Longmans, Green and Co., Inc., New York, 1951. Price, $5.50.

This work delves into the various methods employed in dating the past prior to the time covered by the historic calendars. An attempt is made to correlate time scales arrived at by the different methods. Special attention is paid to archeological aspects with particular attention to early man.

In Part I, which deals with early history and late prehistory, tree-ring analyses and results are discussed. In Part II, Dating the Metal Ages, New and Middle

Stone Ages, and Climatic Phases which Followed the Ice Age, varve methods and results are discussed and interrelated with raised beaches, pollen, botanical, and climatic phases, and their applications to the prehistoric chronology of the post-glacial.

Part III deals with the dating of the old stone age, the ice age, and pluvial phases of the warmer climates. It takes up the relative and absolute chronology of the Pleistocene with considerations of climatic phases, the astronomical theory, and the Paleolithic of different areas of the world, with particular emphasis on early man.

Part IV gives consideration to the history of the earth before the arrival of man by paleontological, radioactive, and biological methods with emphasis on evolution.

An appendix supplies most of the newer information, such as Carbon 14, that has resulted since the first edition of the book in 1945 and since the manuscript of the second edition was completed in 1948.

The book should prove of interest to geologists, botanists, zoologists, and physicists, as well as to all interested in archeology and evolution.

**Geography in the Twentieth Century.** Edited by GRIFFITH TAYLOR. Pp. 630; figs. 56. Philosophical Library, New York, and Methuen, London, 1951. Price, $8.75.

This distinctive book has an unusual approach, a philosophical one. It is one of a series of volumes being issued by the Philosophical Library of New York to discuss the philosophical aspects of the various disciplines in the arts and sciences. Its 26 chapters are the work of 20 geographers, and the Editor contributed six of these.

The book is divided into 3 parts: Part I (Chaps. 1–6), Evolution of Geography and Its Philosophical Basis; Part II (Chaps. 7–16), The Environment as a Factor; Part III (Chaps. 17–26), Special Fields of Geography. The chapters and authors are: 1, Introduction, by G. Taylor; 2, Geography in the Nineteenth Century, by G. Tatham; 3, The French School of Geography, by R. J. Harrison Church; 4, The German School of Geography, by S. van Valkenburg; 5, The West Slav Geographers, by J. Král and J. Kondracki; 6, Environmentalism and Possibilism, by G. Tatham; 7, The Progress of Geomorphology, by S. W. Wooldridge; 8, Geographical Aspects of Meteorology, by F. K. Hare; 9, Climatic Influences, by Stephen S. Visher; 10, Soils and Their Geographical Significance, by D. F. Putnam; 11, Settlement by the Modern Pioneer, by Isaiah Bowman; 12, Geography and Arctic Lands, by A. L. Washburn; 13, Exploration of Antarctica, by G. Taylor; 14, Geography and the Tropics, by Karl J. Pelzer; 15, Geography and Regionalism, by E. W. Gilbert; 16, Land Use Surveys with Special Reference to Britain, by L. Dudley Stamp; 17, Geography is a Practical Subject, by D. F. Putnam; 18, Geography and Empire, by Charles B. Fawcett; 19, Racial Geography, by G. Taylor; 20, The Sociological Aspects of Geography, by J. W. Watson; 21, Urban Geography, by G. Taylor; 22, Geography and Aviation, by Ellsworth Huntington; 23, The Field of the Geographical Society, by J. K. Wright; 24, Geography in Practice in the Federal Government, Washington, by John K. Rose; 25, Geopolitics and Geopacifics, by G. Taylor; 26, A Concise Glossary of Geographical Terms, by G. Taylor.

As may be seen from the titles the coverage is broad and each chapter is written by an expert in the field. The book is one that can be enjoyed by the lay reader as well as by the student of geography.

## BOOKS RECEIVED.

M. L. MIGNONE.

**Bibliography of North American Geology 1949.** EMMA MERTINS THOM, MARJORIE HOOKER, AND RUTH REECE DUNAVEN. Pp. 273. U. S. Geol. Survey Bull. 977, Washington, D. C., 1951. Price, 55 cts. *Newest addition to a very useful series.*

**Geology of Uranium Deposits—A Condensed Version.** DONALD L. EVERHART AND MURIEL MATHEZ. Pp. 33; tbl. 1. U. S. Atomic Energy Commission RMO-732, Oak Ridge, Tenn., May 1951. *Condensation of available data.*

**Proceedings of the Alaskan Science Conference of the National Academy of Sciences, National Research Council, Washington, D. C., November 9–11, 1951.** Pp. 216; map 1. Nat. Research Council Bull. 122, April 1951. Price, $2.00. *Objectives of the Conference, suggested means and abstracts presented.*

**Plane Table Manual for Geologists.** KENNETH K. LANDES. Pp. 17; figs. 3. George Wahr Publishing Co., Ann Arbor, Mich., 1951. *Rules and cautions for triangulation and Beaman stadia traverse, with natural tangent table and curvature and refraction table.*

**California Division of Mines—San Francisco, 1950–1951.**

**Bull. 148. Geology of the Blue Lake Quadrangle, California.** GEORGE A. MANNING AND BURDETTE A. OGLE. Pp. 36; figs. 2; pls. 13. Price, $1.50. *Three formations mapped; complex, repeated faulting; two major periods of faulting; no mineral deposits of economic importance found, only a few minor prospects.*

**Bull. 153. Geology and Mineral Resources of the Neenach Quadrangle, California.** JOHN H. WIESE. Pp. 53; fig. 1; pls. 12; tbls. 2. Price, $1.75. *Descriptive and structural geology, physiography. Only mineral production is from one tin mine and a group of three small gold mines; many small workings on south flank of Tehachapi Range explore gossan, tactite, or quartz bodies with minor gold, tin, tungsten, copper, and iron. No indications of petroleum. Deep ground water supply exploited since 1946.*

**Bull. 155. Minerals Useful to California Agriculture.** Pp. 148; figs. 23; pls. 3; tbls. 17. Price, $1.00. *Nine papers by six authors on: exploring the soils, commercial fertilizers, minerals of commercial fertilizers, agricultural minerals, agricultural gypsum, gypsum resources, limestone and marl, sources of sulfur and sulfuric acid, minerals of minor agricultural use.*

**Bull. 157. Geology of the San Jose-Mount Hamilton Area, California.** MAX D. CRITTENDEN, JR. Pp. 74; figs. 14; pls. 11; tbls. 3. Price, $2.00. *Physiography, stratigraphy, structure, and geologic history; quicksilver deposits in Silver Creek and Oak Hills believed associated with late Pleistocene to Recent volcanism; minor deposits of manganese; good road metal; rip-rap; ground water most important natural resource.*

**California Journal of Mines and Geology, Vol. 47, No. 2, April 1951.** Pp. 347; pls. 12; figs. 3; maps 2. Price, $1.00. *Annual report of state mineralogist chief of the Division of Mines; mineral production and significant mining activities of 1949, county by county; numerous useful tables; directory*

*of producers of metallic and nonmetallic minerals during 1949; directory of mineral dealers and commercial laboratories; list of publications of the Division of Mines.*

**California Journal of Mines and Geology, Vol. 47, No. 3, July 1951.** Pp. 86; map 1; pl. 1; figs. 3. Price, $1.00. *Mineral needs and problems of the bituminous base roofing industry, by Dozier Finley; mines and mineral resources of Fresno County, California, by C. A. Logan, Lewis T. Braun, and James W. Vernon.*

**Ohio Geological Survey—Columbus, 1950–1951.**

**Inf. Circ. 6. Division of Geological Survey Annual Report 1950.** JOHN H. MELVIN. Pp. 16; map 1; photos 12. *Ohio is first in lime, clay and clay products.*

**Rept. Inv. 7. Shore Erosion on Sandusky Bay.** PAUL R. SHAFFER. Pp. 5; fig. 1.

**Canada Geological Survey—Ottawa, 1951.**

**Bull. 18. Contributions to the Paleontology and Stratigraphy of the Jurassic System in Canada.** HANS FREBOLD. Pp. 54; pls. 18; figs. 2. Price, 25 cts. *Ammonite fauna and stratigraphy of the lower lias in Tyaughton Lake, B. C.; revision of "Peltoceras Occidentale" whiteaves from fernie group of upper Red Deer River, Alta.; lowermost middle Jurassic fauna in Whitesail Lake, B. C.*

**Bull. 19. The Correlation, by Petrographic Analyses, of No. 5 Seam in the St. Rose and Chimney Corner Coalfields, Inverness County, Cape Breton Island, Nova Scotia.** P. A. HACQUEBARD. Pp. 33; tbls. 7; pls. 2; figs. 5. Price, 25 cts. *Detailed account of method; specialized technique employed; nomenclature and classification; compilation of coal-seam data, their interpretation and application.*

**Geology of the District North and East of Leeds.** WILFRED EDWARDS, G. H. MITCHELL, AND T. H. WHITEHEAD. Pp. 93; figs. 15; pls. 3. Great Britain Geol. Survey Mem., London, 1950. *Thick seams of coal largely exhausted; lots of burnt lime for building and land-dressing; sand and gravel, gypsum, anhydrite; water is obtained from all formations.*

**Mineral Map of Australia.** N. H. LUDBROOK. 41″ × 30″; scale, 1″ = 75 miles. Bur. Min. Resources, Geol. and Geophysics, Melbourne, January 1950. *Shows principal localities for each mineral and metal.*

**Exploration for Copper in Wallaroo Mining District, South Australia.** V. P. SOKOLOFF. Pp. 11; figs. 6. Chem. Eng. and Min. Rev., June 10, 1951. *A systematic examination of the polymorphic soil mantle in Wallaroo Mining District, South Australia, resulted in discovery of three copper anomalies in the lower soil horizons. The exploratory boring of these anomalies established a sub-economic chalcopyrite mineralization in all at several hundred feet depth. The outcome of the project so far may be described as a technical success (the copper ore was found) but a commercial failure (less than 0.5% chalcopyrite in the ore).*

**Outline of the Geology of Ufipa and Ubende.** R. B. MCCONNELL. Pp. 62; pls. 2; tbl. 1; 2 colored maps. Tanganyika Geol. Survey Bull. 19, Dodoma, 1950. Price, Shs. 15/–. *Physiography, geological formations, structure. Mineral re-*

*sources still largely undeveloped; gold throughout, but small; minor copper, lead, nickel, chromite, asbestos, talc; remarkable deposit of low-grade manganiferous iron ore; several important mica mines described; large undeveloped coal resources.*

**Indian Minerals, Vol. III, No. 4, October, 1949.** Pp. 58; fig. 1; numerous tables. India Geol. Survey, Calcutta. Price, 3 s. *Conservation of mineral resources; field program for 1949–1950; mineral production of the Indian Union in 1948; chromite deposits in the Tiruchengodu and Namakkal Taluks, Salem District.*

**On Some Abandoned Gold Mines in Nilgiri-Wynaad and Their Economic Possibilities.** K. K. SEN GUPTA AND JYOTIRMOY SEN GUPTA. Pp. 39; figs. 21. Geol., Min. Met. Soc. India Quart. Jour., Vol. 22, No. 4, December 1950. Calcutta, Price, Rs. 3. *Estimated reserve 18,000 tons with average yield of 1.6 dwts. per ton.*

**O Congresso Internacional de Geologia de Londres.** ALBERTO RIBEIRO LAMEGO. Pp. 144; photos 10. Div. Geol. e Min. Bol. 132, Rio de Janeiro, 1949. *Translation into Portuguese of numerous abstracts on varied subjects presented in London at the 18th Geological Congress.*

**Notizie Sull'Industria Mineraria Piombo-Argento-Zincifera in Brasile.** PIERO ZUFFARDI. Pp. 24; figs. 5; 6 colored plates. Cagliari, Italy, 1950. *Lead-silver mineral industry of Brazil could be important if developed; possibility of new discoveries.*

**Annales de la Société Géologique de Pologne, Vol. XX, Fasc. 1–2, 1950.** Pp. 212; numerous illustrations. Krakow, 1951. *Ore veins on Ornak in the Western Tatra Mountains; chemical composition of biotites in different rocks of the Tatra Mountains; exotic diabase in the Karpathian Cretaceous; French or English summaries.*

**Bulletin du Muséum d'Histoire Naturelle du Pays Serbe.** Pp. 117; figs. 9; tbls. 4; pls. 8. Belgrade, 1948. *Eight papers on paleontology and two on structural geology. Mineralogy of the Trepča barite. Discovery of a rare mineral: chalcophanite in two Yugoslavian localities; are in veins of oxidized manganese in well propillitized andesites; veins produced by oxidation of deep sulfide lead-zinc minerals.*

# SCIENTIFIC NOTES AND NEWS

JOSIAH THOMAS resigned as manager of the Bolivian subsidiary companies, American Smelting & Refining Co., and accepted the position of general manager, Cia Minera Unificada del Cerro de Potosi, Potosi, Bolivia.

SUMNER M. ANDERSON, chief Latin American Division, Foreign Minerals Region, Bureau of Mines, went to Bolivia to work on problems relating to Point IV assistance in tin metallurgy.

EVERETTE L. DEGOLYER, senior partner, DeGolyer & McNaughton, Dallas, and FREDERICK SEITZ, research professor of physics at the University of Illinois, Urbana, Ill., have been elected to membership in the National Academy of Sciences.

P. C. EMRATH, mining engineer, Marion, Ky., left for Taiwan (Formosa) for the J. G. White Engineering Corporation, New York.

WALLACE G. FETZER has been made chief geologist, western division, Vanadium Corporation of America, Durango, Colo.

GUS H. DOUDARZI is now with the Geological Survey of Gold Coast, Saltpond, Gold Coast.

CHARLES E. HUNTER is now geologist for the Consolidated Feldspar Corporation, Asheville, N. C.

RICHARD T. EVANS and FREDERICK M. HART retired on July 31 from the U. S. Geological Survey after 52 and 51 years service respectively, and were presented with illuminated scrolls, awards for meritorious service and other tokens on behalf of the Survey.

MAURICE L. BRASHEARS, JR., District Geologist, of the Mineola, N. Y., office of the Ground Water Branch, Water Resources Division, U. S. Geological Survey, has returned to the States from his assignment as a Visiting Expert Consultant on Water Supplies to the Supreme Commander of the Allied Forces in the Pacific and to the Japanese Government. After being on leave status for a while, and conferring with Washington office personnel, he resumed his duties at Mineola.

GORDON S. DE VILLIERS, Underground Manager for Anglo-Transvaal Consolidated Investment Company, Ltd., Johannesburg, South Africa, is presently in the United States acting as consultant to the E. J. Longyear Company, Minneapolis, Minnesota. Mr. de Villiers was in charge of the Virginia No. 3 Shaft in the Orange Free State, which in two successive months this year broke the World's Record for shaft sinking, culminating with the accomplishment of 504 feet of sinking and concreting during April 1951.

WILBURN C. SCHROEDER has been appointed as acting administrator of the Defense Minerals Administration in the Department of the Interior replacing DR. JAMES BOYD. He has also been designated Assistant Director of the Bureau of

Mines for Programs. He will thus supervise the personnel of the Defense Minerals Administration and the personnel of the programs divisions and offices of the Bureau of Mines, whose efforts are related to the production and availability of critical materials needed in the defense effort.

SANBORN PARTRIDGE has recently joined the staff of the Department of Geology at Amherst College.

RICHARD V. DIETRICH, who received his Ph.D. this June from Yale University, has accepted a position in the Department of Geology, Virginia Polytechnic Institute, Blacksburg.